TECHNICAL NOTES

U.S. DEPARTMENT OF AGRICULTURE   Boise, Idaho   SOIL CONSERVATION SERVICE

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DESIGN OF POLYVINYL CHLORIDE (PVC) PIPE

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INTRODUCTION

The use of PVC pipe is increasing rapidly for pressurized pipeline systems. Plastic pipe is readily available in sizes up through 12 inches in diameter with larger sizes coming on the market. The Soil Conservation Service is becoming more involved in the application of PVC pipe for sprinkler irrigation systems, and more information is needed in the field on how to evaluate this pipe in quantitative terms. This report has been prepared to discuss some of the more common questions that arise, particularly relating to the criteria given in the National Handbook of Conservation Practices, Standard 430-DD. It is based on published information, technical papers, and personal experience. Included in the report are two calculator programs for the TI-59 programmable calculator which is now being used widely by SCS Engineers. The programs have received limited use and need further testing. Any comments from users would be welcome.

The information presented is not intended to be a complete study on the subject of waterhammer or on external design of pipelines. Both subjects are complex and are affected by a great many variables and uncertainties. Experience has shown that shortcuts can be made in actual practice that greatly simplify the calculations. However, it is necessary that a certain amount of conservatism be applied when bypassing the more rigorous analysis to compensate for variables that are not evaluated. It is believed that the information presented will be conservative for normal SCS applications providing that proper engineering judgment is applied in evaluating the remaining variables.

WATERHAMMER

GENERAL

National Handbook of Conservation Practices, Standard 430-DD describes the design criteria and limitations of high pressure plastic pipe and appurtenances used in irrigation systems. In the section on Working Pressures and Flow Velocity, it says, "As a safety factor against surge or waterhammer, the working pressure should not exceed 72 percent of the pressure rating of the pipe, and the design flow velocity at system capacity shall not be greater than 5 feet per second. If either of these limits is exceeded, special consideration must be given to the flow condition and measures to adequately protect the pipeline against surge." The purpose of this discussion is to expand on the reasons for these limitations, to discuss protective measures, and to show calculation procedures for waterhammer in PVC pipe. Included as Appendix 4 is a paper entitled

"Waterhammer Calcuations for PVC Pipelines in Irrigation Systems", by W. R. Seipt. This paper is an excellent discussion for the subject and is the basis for much of the material in this Technical Note.

In the simplest terms, waterhammer occurs when water flowing under pressure in a pipeline is subjected to a change in velocity. The energy contained in the flowing water causes pressure surges as the velocity change takes place and a new energy balance is being established. The magnitude of the pressure surges, or waterhammer, depends to some extent upon how fast the velocity change occurs.

Pressure surges as high as 15 times the initial pressures have been recorded in laboratory tests. These surges travel up and down the pipeline from end to end at sonic velocities, the magnitude remaining fairly constant dampened only by water and irregularities in the pipe, pressure relief valves, bends, reductions in pipe size, and interference with reflected waves.

CAUSES AND PROTECTIVE MEASURES

The more common causes of velocity change in a constant size pipeline are listed below:

1. Opening or closing a valve.
2. Starting or stopping a pump.
3. Movement of air along a pipeline.
4. Sudden or rapid removal of air from a pipeline.
5. Water columns that had been separated in a pipe length coming back together.
6. Rapid filling of an empty pipeline.

Opening or Closing Valves

The most common activity along a pipeline is the operation of valves. The movement of these valves can cause substantial changes in pipe flows and velocities. If the valves are moved rapidly, serious surge pressures can be induced into the system. To minimize this risk, designers commonly employ gear driven valve operators which require a significant number of revolutions to move the valve from open to closed position, which takes a predictable amount of time to accomplish. It is common to find that closing times may range from 60 seconds to 5 minutes or more to keep the pressure rise at acceptable levels. Quick closing valves or butterfly valve operators that move only 90 degrees from full open to full closed are not recommended.

Starting or Stopping Pumps

Pump operations can cause excessive pressure surges in the pipeline system. Starting up can send a large volume of water up the pipe at a rate that does not allow time for air to be exhausted through air vacuum valves at high points or at ends of lines. The impact as water hits this air cushion can cause surges as well as when the air begins to move up or out of the pipe after the water has come to a stop. Since air can move so much faster than water, a substantial surge can occur when water flows to fill a void created when the air moves.

Shutting down a pump creates a different but equally dangerous situation. The flow of water in the pipe must come to a stop and reverse directions to flow back towards the pump. If the pipe profile is undulating, then flow may reverse directions in several sections of pipe. All of these locations could experience pressure surges under certain conditions when a column of water impacts upon another column of water or upon some solid object such as a regulating valve, pipe end, or a check valve.

The problem of pump operation is magnified if pumps are subject to power outages and can restart automatically without substantial delay when power is restored. If flow is occurring in the reverse direction when the pump restarts and introduces a fresh surge of direction changes, the pressure surge can be dramatic. In addition, since water still fills the low areas in the pipeline, the new flows will impact the standing water much as it would hit a dead end, or, even worse, a substantial cushion of air may be trapped between the two columns of water. This situation becomes explosive as the pressure builds and the air compresses, then suddenly moves toward a high point in the pipeline.

The most common means of alleviating these kinds of problems includes the use of spring-loaded check valves at the pump which will close before flow reversal takes place when the pump shuts down. An even better device is a solenoid operated valve that automatically closes as soon as the power goes off and before the flow reversal begins. In both of these measures, the idea is to keep the pipe full of water, not allowing reverse flow or water column separation when the pump shuts down. If automatic restarting is not needed, a good practice is to install a manual valve near the pump and always start it against a closed valve which can be gradually opened at an acceptable rate of filling for the pipe. The designer of this type of system must be sure that the pump and motor selected will not be damaged by operation in this manner.

Other devices such as time delay relays, pumps that allow backflow through them, and surge anticipation valves, surge tanks, and pressure relief valves are used to limit pressure surges to acceptable levels.

Movement of Air Along a Pipeline

Virtually all irrigation water contains some percentage of dissolved air. A poorly designed intake structure of pump intake system can contribute additional quantities of air which will tend to come out of solution as the pressure in the system fluctuates. The air accumulates along the top of the pipe and works toward high points where, hopefully, continuous acting air-vacuum release valves have been installed to remove the air in an orderly fashion. Unfortunately, for reasons that are not completely understood, the air sometimes collects into sizeable pockets along the top of the pipe and then suddenly "squirts" to another location. The air moves so much faster than water that a void is created and water rushes from all directions to fill the void literally crashing into the pipe walls and into itself. In some cases, this can cause substantial pressure surges. Obviously, this problem is much more common in pipelines built on very flat terrain where the air can accumulate over long sections before collective movement occurs.

Sudden or Rapid Removal of Air From a Pipeline

If a sizeable air pocket is allowed to accumulate in a pipeline, then compressed as pressure is applied, a highly explosive pressure surge will occur if the air is suddenly evacuated. Some farmers have been unwilling witnesses to this type of surge when they opened an irrigation riser in a section of pipe where air has accumulated. Manually operated air release valves are not recommended for this reason. It is essential that all possible precautions be taken in design and installation to prevent "traps" where air can accumulate during pipeline operation. If the pipe is carefully laid to a uniform grade with continuous acting air-vacuum valves at all high points, this problem should be minimized. In the case of very flat grades, additional air-vacuum valves may be installed at 1000 foot to 1500 foot intervals.

Water Column Separation

Water column separation is generally associated with starting or stopping pumps but may occur under other conditions. If the demand for water out of a system fluctuates widely, pressures could drop enough at some high points to create a slight vacuum and cause an air-vacuum valve to inject air into the pipe. Other examples would be when a gravity inlet to the pipe experiences intermittent plugging with debris or when a fluctuating water supply does not provide enough water to keep up with the demand at all times. Once the air is trapped inside the pipeline, then the situation is as described in the two preceeding sections. The best solution to this problem is to prevent the introduction of air into the system if at all possible, through better design at the inlet and better operating procedures to prevent widely fluctuating flows.

Rapid Filling of an Empty Pipeline

Many experienced pipeline designers feel that the most critical time in the life of a pipeline is during the filling process. It is during this time that the opportunity for pressure surges is greatest because air is being evacuated as the pipe fills. Low points in the line fill first and create a series of separated water columns in the pipe. If the filling rate is greater than the capacity of the air-vacuum valves to remove air or if any air-vacuum valve malfunctions, then substantial air pockets may be trapped in the line as the pressure rises with all the dangers previously described. It is essential that pipelines be filled slowly and carefully, with someone checking each air-vacuum valve as it is evacuating the air to be sure that it functions properly and doesn't close until all the air is gone.

DESIGN CRITERIA

In an attempt to avoid the tedious and difficult computations for waterhammer in routine pipeline design, PVC pipe manufacturers have made recommendations of limits for designers to use that should provide an adequate safety factor to accommodate surges under normal conditions. The values quoted from the NHCP represent these recommendations and have been widely used by designers both in and out of SCS with good success.

In many cases it is not possible or practical to design within the general limits described in Standard 430-DD. The project may be more complex and should be considered as beyond the "normal conditions" suitable for using generalized assumptions.

When this occurs, the standard allows the designer to make a more detailed analysis. "If either of these limits are exceeded (design pressure exceeds 72 percent of the pressure rating of the pipe or velocity exceeds 5 feet per second), special consideration must be given to the flow conditions and measures to adequately protect the pipeline against surge."

A realistic review of the causes of velocity change reveals that once the air-vacuum valves and pressure relief valves are in place, nearly everything else hinges on the operation of the system by the users. If a pump supplies the pressure, then stopping and starting the pump is a critical factor in the evaluation. The operation of valves and filling procedures are critical factors in both pumped and gravity pipelines. The designer must make an honest appraisal of expected operation procedures before a meaningful calculation of waterhammer can be made.

WATERHAMMER CALCULATIONS

Determination of the actual amount of pressure rise due to waterhammer will usually clarify what remedial measures may be needed to assure safe operation of the pipeline. Often the decision is an economic one comparing the costs and benefits of installing a stronger pipe versus slow-closing valves or a combination of both.

Generalized equations for the calculation of pressure rise due to waterhammer are rather cumbersome, but can be simplified considerably when evaluating PVC pipe specifically. When considering instantaneous closure (defined as when the velocity change occurs in less than $2L/a$), the pressure rise is simply 79.22 times the change in velocity divided by $(SDR-0.443)^{\frac{1}{2}}$ where L is the length of pipeline affected by the pressure surge, in feet; a is the velocity of the pressure surge in the pipe, in feet per second; and SDR is the standard dimension ratio or the ratio of outside diameter to wall thickness. This means that water flowing to a dead end of a pipe or by closing a valve in less time than double* that calculated above will create an increase in pressure in the pipe to the magnitude calculated. The PVC pipe to be used in this case must have a pressure rating greater than the sum of the operating pressure plus the calculated pressure rise.

If the velocity change occurs in a longer time than that calculated above, the magnitude of pressure increase may be substantially less than for instantaneous closure. The pressure rise is usually determined for this condition by calculating coefficients required to enter a chart such as the Allievi Chart. A valve closing time is required in determining the coefficients. The chart yields a percent of pressure rise which can easily be converted to feet and/or psi for a problem at hand. Again, this value is added to the operating pressure required and a pipe is selected with a pressure rating greater than the total pressure. As an alternative, a slower valve closing time may be selected and the procedure used to find the resulting pressure rise. This process may be continued to find the most practical combination of pipe strength and valve closing time. Care must be taken to insure that the selected valve closing time* is one that can realistically be expected to occur in actual practice.

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*The actual closing time must be double that used in calculations because more than 90 percent of the velocity change will take place while closing the valve only 50 percent for most types of valves.

A program has been developed for the TI-59 programmable calculator (Appendix 1) to perform the pressure rise calculations described above for PVC pipe. It is also designed to perform the hydraulic calculations for PVC pipe in accordance with the criteria in NHCP. The user can either solve for flow rate, Q, or for head loss due to friction, H_L, for a given set of conditions. Successive trials with varying conditions can be easily performed.

The waterhammer analysis is straight forward but is limited to single pipe sizes and requires the use of the Allievi Chart (Appendix 2) to find the percent pressure rise for timed closures greater than the critical closure time. Idaho Appendix #4 to the Engineering Field Manual (Appendix 3) provides needed PVC pipe properties to use in the input data. Several trials of pipe sizes and pressure ratings can be performed rapidly to find the best combination of pipe strength and valve opening speeds.

See Tech note 7

EXTERNAL LOAD DESIGN OF FLEXIBLE PIPES

GENERAL

It is common practice to specify a minimum depth of cover over pipelines without any further concern about the supporting strength of the pipe. As more pipe failures are being reported, it is becoming apparent that designers should take a look at the external loads that are being applied to the pipelines and determine that the pipe has adequate strength to support that load.

Buried flexible pipes derive their ability to support external loads from their inherent strength plus the passive resistence pressure of the soil as they deflect and the sides of the pipe move outward against the soil side fills. This type of pipe fails by excessive deflection and collapsing or buckling rather than by rupturing of the pipe walls as in the case of pipes made of brittle materials. For these reasons it is essential that the designers and constructors have a common understanding of the nature of the bedding and backfill material around the pipe. Specifications must be clearly written so that the contractor can install the material as the designer intended to give adequate support to the pipe walls.

From this it can be seen that the design of flexible pipes is directed toward determination of the amount of deflection that can be expected to occur, given the loads and strength of the pipe and soil around the sides.

DESIGN PROCEDURE

The Modified Iowa Formula is one of the most widely used equations for finding the amount of deflection in flexible pipes. Its solution yields the deflection in the horizontal direction. Since the pipeline designer needs to know the vertical deflection, a simple relationship exists in that the vertical deflection is approximately 10% greater than the horizontal deflection. The Modified Iowa Formula is generally written:

$$\Delta X = \frac{D_L\ (K)\ (WC)\ r^3}{EI + 0.061\ (E')\ r^3}$$

Where: D_L = Deflection lag factor

K = Bedding constant

WC = Total load on the pipe, in pounds per linear inch

r = Mean radius of the pipe, in inches

E = Modulus of elasticity of the pipe material, in psi

I = Moment of inertia of the pipe wall per unit length, in inches^3

E' = Modulus of soil reaction, in psi

ΔX = Horizontal deflection or change in diameter, in inches

The deflection lag factor is an empirical value selected to compensate for the time period over which the pipe will continue to deflect. It ranges from 1.25 to 1.5.

The bedding constant depends upon the angle subtended by the pipe bedding and ranges between 0.08 and 0.110.

The load on the pipe, WC, is composed of the sum of the superimposed live load and the weight of the soil on top of the pipe. The live load usually ranges between 16,000 pounds (HS-20) and 10,000 pounds. An impact factor is commonly applied to live loads for pipes with less than four feet of cover. This factor usually ranges from 1.1 to 1.5. The dead load used in this equation is the weight of a prism of soil over the pipe. No adjustment is made for varying trench widths as in the Spangler equations.

The modulus of soil reaction has been derived empirically by examining over 1000 buried pipes. It has a significant effect on the deflection of the pipe and must be carefully selected to represent actual field conditions. It is essential that the specifications and on-site inspection be adequate to insure that the installation will achieve the conditions assumed for the soil modulus selected. A program for the TI-59 has been prepared (Appendix 5) to solve the Modified Iowa Equation with a minimum of input data by the user. Conservative values have been pre-selected for the deflection lag factor and the bedding constant and inserted in the program. The program automatically calculates the vertical deflection in percent and in inches based on the users input conditions.

APPENDIX

1. TI-59 Program for PVC Pipe Hydraulics and Waterhammer Analysis.
2. Allievi Chart for Finding Pressure Rise Due to Waterhammer.
3. Plastic Pipe Dimensions, Idaho Appendix #4, Engineering Field Manual.
4. "Waterhammer Calculation for PVC Pipeline in Irrigation Systems", by W.R. Seipt.
5. TI-59 Program for External Load Design in Flexible Pipe.

Appendix 1

TITLE PVC PIPE HYDRAULICS AND WATERHAMMER ANALYSIS PAGE 1 OF 4

TI Programmable Program Record

PROGRAMMER Karl Larson DATE Nov. 1981

Partitioning (Op 17) 6 3 9 . 3 9 Library Module No Printer Yes Cards 2-4 sides

PROGRAM DESCRIPTION

User can solve for either flow rate, Q, or head loss, H_L, in the hydraulic portion of the program. Basic equations are the Hazen-Williams using a coefficient of 150.

$$Q = 1.318\ (C)\ (A)\ (R^{.63})\ (S^{.54}) \quad \text{and} \quad H_L = \frac{4.73\ (L)\ (Q^{1.852})}{C^{1.852}\ (D^{4.87})}$$

To find Q, the user must input the inside pipe diameter in inches, and the slope of the hydraulic grade line in feet/foot. To find head loss, the user must input pipe length in feet and pipe diameter in inches. The calculator finds the unknowns and prints pipe cross-sectional area and velocity.

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1.	Set partition	4	2nd	OP	17	639.39
2.	Insert Magnetic Cards- 2 cards both sides	1,2,3,4				1.,2.,3.,4.
3.	TO FIND Q					
	a. Input inside pipe diameter in inches		A			Prints DIA
	b. Input slope of HGL, in ft./ft.		B			Prints S
	c. To begin calcs for Q, in cfs		D			Prints Q
	Finds pipe cross-sect. area, in square feet					Prints A
	Finds flow velocity, in feet per second					Prints V
4.	TO FIND HEAD LOSS					
	a. Input pipe length in feet		2nd	A		Prts L
	b. Input pipe diameter in inches			R/S		Prts DIA (in Ft)
	c. Input Q in cfs			R/S		Prts Q
	calculates head loss in feet					Prts HL
	calculates cross-sect. area in sq. ft.					Prts A
	calculates velocity in feet per second					Prts. V

USER DEFINED KEYS	DATA REGISTERS (INV Int)		LABELS (Op 08)
A	0	0	INV _ lnx _ CE _ CLR _ x:t _ x² _
B	1	1	√x _ 1/x _ STO _ RCL _ SUM _ yˣ _
C	2	2	EE _ (_) _ ÷ _ GTO _ × _
D	3	3	SBR _ − _ RST _ + _ R/S _ . _
E	4	4	+/− _ = _ CLR _ _ _ _
A'	5	5	
B'	6	6	
C'	7	7	
D'	8	8	
E'	9	9	

FLAGS 0 1 2 3 4 5 6 7 8 9

TITLE PVC PIPE HYDRAULICS AND WATERHAMMER ANALYSIS

PAGE 1 OF 4

TI Programmable Coding Form

PROGRAMMER Karl Larson

DATE Nov. 1981

LOC	CODE	KEY	COMMENTS
000	76	LBL	Input I.D.
001	11	A	in inches
002	99	PRT	
003	55	÷	
004	01	1	
005	02	2	
006	95	=	
007	42	STO	
008	00	00	
009	01	1	
010	06	6	
011	02	2	
012	04	4	
013	01	1	
014	03	3	
015	69	OP	
016	04	04	
017	43	RCL	
018	00	00	
019	69	OP	
020	06	06	Prts DIA
021	91	R/S	
022	76	LBL	Input slope
023	12	B	of HGL
024	42	STO	
025	01	01	
026	03	3	
027	06	6	
028	69	OP	
029	04	04	
030	43	RCL	
031	01	01	
032	69	OP	
033	06	06	Prt. S
034	91	R/S	
035	76	LBL	Input SDR
036	13	C	
037	42	STO	
038	02	02	
039	03	3	
040	06	6	
041	01	1	
042	06	6	
043	03	3	
044	05	5	
045	69	OP	
046	04	04	
047	43	RCL	
048	02	02	
049	69	OP	
050	06	06	Prts SDR
051	91	R/S	
052	76	LBL	
053	14	D	

LOC	CODE	KEY	COMMENTS
055	01	01	
056	45	Y^X	
057	93	.	
058	05	5	
059	04	4	
060	95	=	
061	65	×	
062	53	(	
063	43	RCL	
064	00	00	
065	55	÷	
066	04	4	
067	54	)	
068	45	Y^X	
069	93	.	
070	06	6	
071	03	3	
072	95	=	
073	65	×	
074	43	RCL	
075	00	00	
076	33	X^2	
077	55	÷	
078	04	4	
079	65	×	
080	89	π	
081	65	×	
082	01	1	
083	09	9	
084	07	7	
085	93	.	
086	07	7	
087	95	=	
088	42	STO	
089	03	03	
090	03	3	
091	04	4	
092	69	OP	
093	04	04	
094	43	RCL	
095	03	03	
096	69	OP	
097	06	06	Prts Q
098	43	RCL	
099	00	00	
100	33	X^2	
101	55	÷	
102	04	4	
103	65	×	
104	89	π	
105	95	=	
106	42	STO	
107	04	04	
108	01	1	

LOC	CODE	KEY	COMMENTS
110	69	OP	
111	04	04	
112	43	RCL	
113	04	04	
114	69	OP	
115	06	06	Prts A
116	35	1/X	
117	65	×	
118	43	RCL	
119	03	03	
120	95	=	
121	42	STO	
122	05	05	
123	04	4	
124	02	2	
125	69	OP	
126	04	04	
127	43	RCL	
128	05	05	
129	69	OP	
130	06	06	Prts V
131	91	R/S	
132	76	LBL	Input pip
133	15	E	length
134	42	STO	
135	06	06	
136	02	2	
137	07	7	
138	69	OP	
139	04	04	
140	43	RCL	
141	06	06	
142	69	OP	
143	06	06	Prts L
144	43	RCL	
145	02	02	
146	75	-	
147	93	.	
148	04	4	
149	04	4	
150	03	3	
151	95	=	
152	34	√X	
153	35	1/X	
154	65	×	
155	05	5	
156	08	8	
157	09	9	
158	02	2	
159	95	=	

MERGED CODES

62 | 63 | 64 | 72 STO | 73 RCL | 74 SUM | 83 GTO | 84 | 92 INV SBR

TEXAS INSTRUMENTS INCORPORATED

TITLE PVC PIPE HYDRAULICS AND WATERHAMMER ANALYSIS PAGE 2 OF 4 Appendix 1

TI Programmable Program Record

PROGRAMMER Karl Larson DATE Nov. 1981

Partitioning (Op 17) 6 3 9 3 9 Library Module No Printer Yes Cards 2-4sides

PROGRAM DESCRIPTION

Waterhammer program is based on a constant size pipe and a definable length. User must input the outside diameter-wall thickness ratio (SDR) for the trial run, the expected velocity change, and the length of pipe. The calculator finds the critical closure time (2L/A) and the magnitude of pressure rise for the so-called "instantaneous closure". User can then input the designed operating pressure and the calculator will find the velocity of the pressure wave, C, and the pipeline constant, K. User then inputs the trial closure time (which must be greater than the instantaneous time found above) and the calculator finds the time constant, R. The values of K and R are used in the Allievi Chart to find the percent of pressure rise, which is inputted in the program and the calculator then finds the actual pressure rise in feet, in psi, and the total pressure on the system.

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1.	Input expected velocity change		2nd	D		Prints DELV
2.	Input trial SDR			C		Prints SDR
3.	Input length of pipe in feet			E		Prints L
	a. Calculator finds critical closure time					Prints 2L/A
	b. " finds magnitude of pressure rise in psi					Prints DELP
4.	Input design operating pressure in psi		2nd	B		Prts HO (in feet
	a. Calculates velocity of the shock wave					Prts C
	b. Finds pipeline constant, K					Prts K
5.	Input trial valve closure time in seconds		2nd	C		Prts TC
	a. Calculates time constant, R					Prts R
6.	Using K and R in the Allievi Chart, find the pressure rise, N, in percent					
7.	Input N from the Allievi Chart			R/S		Prts N
	a. Calculates the actual pressure rise in feet					Prts HFT
	b. Finds pressure rise in psi					Prts HPSI
	c. Finds total pressure on the pipe system					Prts HTOT

CAUTION: THIS PROGRAM CANNOT BE USED FOR ANY OTHER PIPE THAN PVC AS A NUMBER OF CONSTANTS BUILT INTO THE PROGRAM ARE INCORRECT FOR OTHER MATERIALS.

USER DEFINED KEYS	DATA REGISTERS (INV)		LABELS (Op 08)
A	0	0	
B	1	1	
C	2	2	
D	3	3	
E	4	4	
A'	5	5	
B'	6	6	
C'	7	7	
D'	8	8	
E'	9	9	

FLAGS 0 1 2 3 4 5 6 7 8 9

TITLE PVC PIPE HYDRAULICS AND WATERHAMMER ANALYSIS PAGE 2 OF 4

PROGRAMMER Karl Larson DATE Nov 1981

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS
160	35	1/X	
161	65	×	
162	02	2	
163	65	×	
164	43	RCL	
165	06	06	
166	95	=	
167	42	STO	
168	07	07	
169	00	0	
170	03	3	
171	02	2	
172	07	7	
173	06	6	
174	03	3	
175	01	1	
176	03	3	
177	69	OP	
178	04	04	
179	43	RCL	
180	07	07	
181	69	OP	
182	06	06	Prts 2L/A
183	43	RCL	
184	02	02	
185	75	-	
186	93	.	
187	04	4	
188	04	4	
189	03	3	
190	95	=	
191	34	√X	
192	35	1/X	
193	65	×	
194	43	RCL	
195	18	18	
196	65	×	
197	07	7	
198	09	9	
199	93	.	
200	02	2	
201	02	2	
202	95	=	
203	42	STO	
204	08	08	
205	01	1	
206	06	6	
207	01	1	
208	07	7	
209	02	2	
210	07	7	
211	03	3	
212	03	3	
213	69	OP	

LOC	CODE	KEY	COMMENTS
215	43	RCL	
216	08	08	
217	69	OP	
218	06	06	Prts DFLP
219	91	R/S	
220	76	LBL	Input pipe
221	16	A'	length
222	42	STO	
223	06	06	
224	02	2	
225	07	7	
226	69	OP	
227	04	04	
228	43	RCL	
229	06	06	
230	69	OP	
231	06	06	Prts L
232	91	R/S	
233	55	÷	
234	01	1	
235	02	2	
236	95	=	
237	42	STO	
238	00	00	
239	01	1	
240	06	6	
241	02	2	
242	04	4	
243	01	1	
244	03	3	
245	69	OP	
246	04	04	
247	43	RCL	
248	00	00	
249	69	OP	
250	06	06	Prts DIA
251	91	R/S	
252	42	STO	Input Q
253	03	03	
254	03	3	
255	04	4	
256	69	OP	
257	04	04	
258	43	RCL	
259	03	03	
260	69	OP	Prts Q
261	06	06	
262	45	Y^X	
263	01	1	
264	93	.	
265	08	8	
266	05	5	
267	02	2	
268	95	=	

LOC	CODE	KEY	COMMENTS
270	93	.	
271	00	0	
272	00	0	
273	00	0	
274	04	4	
275	04	4	
276	65	×	
277	43	RCL	
278	06	06	
279	55	÷	
280	53	(	
281	43	RCL	
282	00	00	
283	45	Y^X	
284	04	4	
285	93	.	
286	08	8	
287	07	7	
288	54	)	
289	95	=	
290	42	STO	
291	09	09	
292	02	2	
293	03	3	
294	02	2	
295	07	7	
296	69	OP	
297	04	04	
298	43	RCL	
299	09	09	
300	69	OP	
301	06	06	Prts HL
302	61	GTO	
303	00	00	
304	98	98	
305	76	LBL	Input Operating
306	17	B'	pressure in psi
307	65	×	
308	02	2	
309	93	.	
310	03	3	
311	01	1	
312	95	=	
313	42	STO	
314	10	10	
315	02	2	
316	03	3	
317	03	3	
318	02	2	
319	69	OP	

MERGED CODES

62 · 63 · 64 · 72 STO · 73 RCL · 74 SUM · 83 GTO · 84 · 92 INV SBR

TEXAS INSTRUMENTS

TITLE PVC PIPE HYDRAULICS AND WATERHAMMER ANALYSIS

TI Programmable Program Record

PROGRAMMER Karl Larson DATE Nov 1981

Partitioning (Op 17) 6 3 9 3 9 Library Module No Printer Yes Cards 2

PROGRAM DESCRIPTION

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS	DISPLAY

TYPICAL OUTPUT — Calculations for Flow

11.64	
0.97	DIA
0.01	S
4.977467319	Q
.7389811319	A
6.735581065	V

TYPICAL OUTPUT — Calculations for Head Loss

1320.	L
0.97	DIA
5.	Q
13.27213253	HL
.7389811319	A
6.766072615	V

TYPICAL OUTPUT — Waterhammer Calculations

6.8	DELV
41.	SDR
1320.	L
2.853475185	2L/A
84.58840567	DELP
150.15	HD
925.1876498	C
.6506201892	K
20.	TC
7.008997347	R
1.11	N
16.5165	HFT
7.15	HPSI
72.15	HTOT

USER DEFINED KEYS	DATA REGISTERS (INV [illegible])		LABELS (Op 08)
A	0	0	INV lnx CE CLR x:t x²
B	1	1	√x 1/x STO RCL SUM yˣ
C	2	2	EE ( ) ÷ GTO ×
D	3	3	SBR − RST + R/S .
E	4	4	+/- = [illegible]
A'	5	5	[illegible]
B'	6	6	[illegible]
C'	7	7	[illegible]
D'	8	8	[illegible]
E'	9	9	[illegible]

FLAGS 0 1 2 3 4 5 6 7 8 9

TITLE PVC PIPE HYDRAULICS AND WATERHAMMER ANALYSIS PAGE 3 OF 4

TI Programmable Coding Form

PROGRAMMER Karl Larson DATE Nov 1981

LOC	CODE	KEY	COMMENTS
320	04	04	
321	43	RCL	
322	10	10	
323	69	OP	
324	06	06	
325	43	RCL	
326	02	02	
327	75	-	
328	93	.	
329	04	4	
330	04	4	
331	03	3	
332	95	=	
333	34	√X	
334	35	1/X	
335	65	×	
336	05	5	
337	08	8	
338	09	9	
339	02	2	
340	95	=	
341	42	STO	
342	11	11	
343	01	1	
344	05	5	
345	69	OP	
346	04	04	
347	43	RCL	
348	11	11	
349	69	OP	
350	06	06	
351	65	×	
352	43	RCL	
353	18	18	
354	55	÷	
355	06	6	
356	04	4	
357	93	.	
358	04	4	
359	55	÷	
360	43	RCL	
361	10	10	
362	95	=	
363	42	STO	
364	12	12	
365	02	2	
366	06	6	
367	69	OP	
368	04	04	
369	43	RCL	
370	12	12	
371	69	OP	
372	06	06	
373	91	R/S	
374	76	LBL	
375	18	C'	
376	42	STO	
377	18	18	
378	03	3	
379	07	7	
380	01	1	
381	05	5	
382	69	OP	
383	04	04	
384	43	RCL	
385	18	18	
386	69	OP	
387	06	06	
388	65	×	
389	43	RCL	
390	11	11	
391	55	÷	
392	02	2	
393	55	÷	
394	43	RCL	
395	06	06	
396	95	=	
397	42	STO	
398	13	13	
399	03	3	
400	05	5	
401	69	OP	
402	04	04	
403	43	RCL	
404	13	13	
405	69	OP	
406	06	06	
407	91	R/S	
408	42	STO	
409	14	14	
410	03	3	
411	01	1	
412	69	OP	
413	04	04	
414	43	RCL	
415	14	14	
416	69	OP	
417	06	06	
418	75	-	
419	01	1	
420	95	=	
421	65	×	
422	43	RCL	
423	10	10	
424	95	=	
425	42	STO	
426	15	15	
427	02	2	
428	03	3	
429	[illegible]	[illegible]	
430	01	1	
431	03	3	
432	07	7	
433	69	OP	
434	04	04	
435	43	RCL	
436	15	15	
437	69	OP	
438	06	06	
439	55	÷	
440	02	2	
441	93	.	
442	03	3	
443	01	1	
444	95	=	
445	42	STO	
446	16	16	
447	02	2	
448	03	3	
449	03	3	
450	03	3	
451	03	3	
452	06	6	
453	02	2	
454	04	4	
455	69	OP	
456	04	04	
457	43	RCL	
458	16	16	
459	69	OP	
460	06	06	
461	85	+	
462	53	(	
463	43	RCL	
464	10	10	
465	55	÷	
466	02	2	
467	93	.	
468	03	3	
469	01	1	
470	54	)	
471	95	=	
472	42	STO	
473	17	17	
474	02	2	
475	03	3	
476	03	3	
477	07	7	
478	03	3	
479	02	2	

MERGED CODES

62 | 72 STO | 83 GTO
63 | 73 RCL | 84
64 | 74 SUM | 92 INV SBR

TITLE PVC PIPE HYDRAULICS AND WATERHAMMER ANALYSIS

Appendix 1

PAGE 4 OF 4

TI Programmable Program Record

PROGRAMMER Karl Larson DATE Nov 1981

Partitioning (Op 17) 6 3 9 3 9 Library Module No Printer Yes Cards 2

PROGRAM DESCRIPTION

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS	DISPLAY

LABELS USED

001	11	A
023	12	B
036	13	C
053	14	D
133	15	E
221	16	A'
306	17	B'
375	18	C'
490	19	D'

USER DEFINED KEYS

A
B
C
D
E
A'
B'
C'
D'
E'

DATA REGISTERS (INV Int)

0	0
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	9

LABELS (Op 08)

INV lnx CE CLR x:t x²
√x 1/x STO RCL SUM yˣ
EE ( ) ÷ GTO ×
SBR − RST + R/S .
+/- =

TITLE PVC PIPE HYDRAULICS AND WATERHAMMER ANALYSIS PAGE 4 OF 4

TI Programmable Coding Form

PROGRAMMER Karl Larson DATE Nov 1981

LOC	CODE	KEY	COMMENTS
480	03	3	
481	07	7	
482	69	DP	
483	04	04	
484	43	RCL	
485	17	17	
486	69	DP	
487	06	06	Prts HTOT
488	91	R/S	
489	76	LBL	Inputs change
490	19	D'	in velocity
491	42	STD	
492	18	18	
493	01	1	
494	06	6	
495	01	1	
496	07	7	
497	02	2	
498	07	7	
499	04	4	
500	02	2	
501	69	DP	
502	04	04	
503	43	RCL	
504	18	18	
505	69	DP	
506	06	06	Prts DELV
507	91	R/S	

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

STATE		PROJECT		
Idaho		All Jobs		
BY KDL	DATE 4/2/82	CHECKED BY	DATE	JOB NO.
SUBJECT PVC Pipe Hydraulics and Waterhammer Analysis				SHEET 1 OF 2

EXAMPLE PROBLEM

Given: Design operating pressure = 65 psi

Trial Pipe Diameter = 12" Nominal PIP, SDR = 41
Slope of Hydraulic Grade Line = .01 ft/ft
Length of Pipeline = 1,320 feet.

Procedure

1. From Appendix 3, find inside diameter is 11.64 inches. Input 11.64, Press A.

2. Input 0.01, Press B.

3. Press D.

Results

1. Calculator prints out 4.977 cfs.

2. Cross-section area of pipe = 0.739 feet.

3. Flow Velocity is 6.736 feet/second.

Check waterhammer for a valve closure at the end of the pipeline.

1. Input change in velocity = 6.8, Press second D.

2. Input SDR = 41, Press C.

3. Input length of pipe, L = 1320, Press E.

4. Calculator prints out critical closure time, 2L/A = 2.85 seconds.

5. Calculator prints out the pressure rise, DELP, for any valve closure time less than the critical time. DELP = 84.59 psi

   NOTE: This pressure rise could be expected if the pipe were filled too rapidly with the design Q against a closed valve or the deadend of the pipe, as well as when closing the valve in less than 2.85 seconds. (Actually the minimum closure time is 2.85 x 2 = 5.70 seconds. See footnote on page 5 of Technical Note.)

COMPUTATION SHEET
SCS-ENG-523 Rev. 8-69

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

STATE Idaho		PROJECT All Jobs		
BY KDL	DATE 4/2/82	CHECKED BY	DATE	JOB NO.
SUBJECT PVC Pipe Hydraulics and Waterhammer Analysis				SHEET 2 OF 2

6. Check effect of slower valve closure. Input design operating pressure = 65 psi. Press second B.

7. Calculator prints shock wave velocity and the pipeline constant, K = 0.65.

8. Input trial valve closure time = 20 seconds. Press second C.

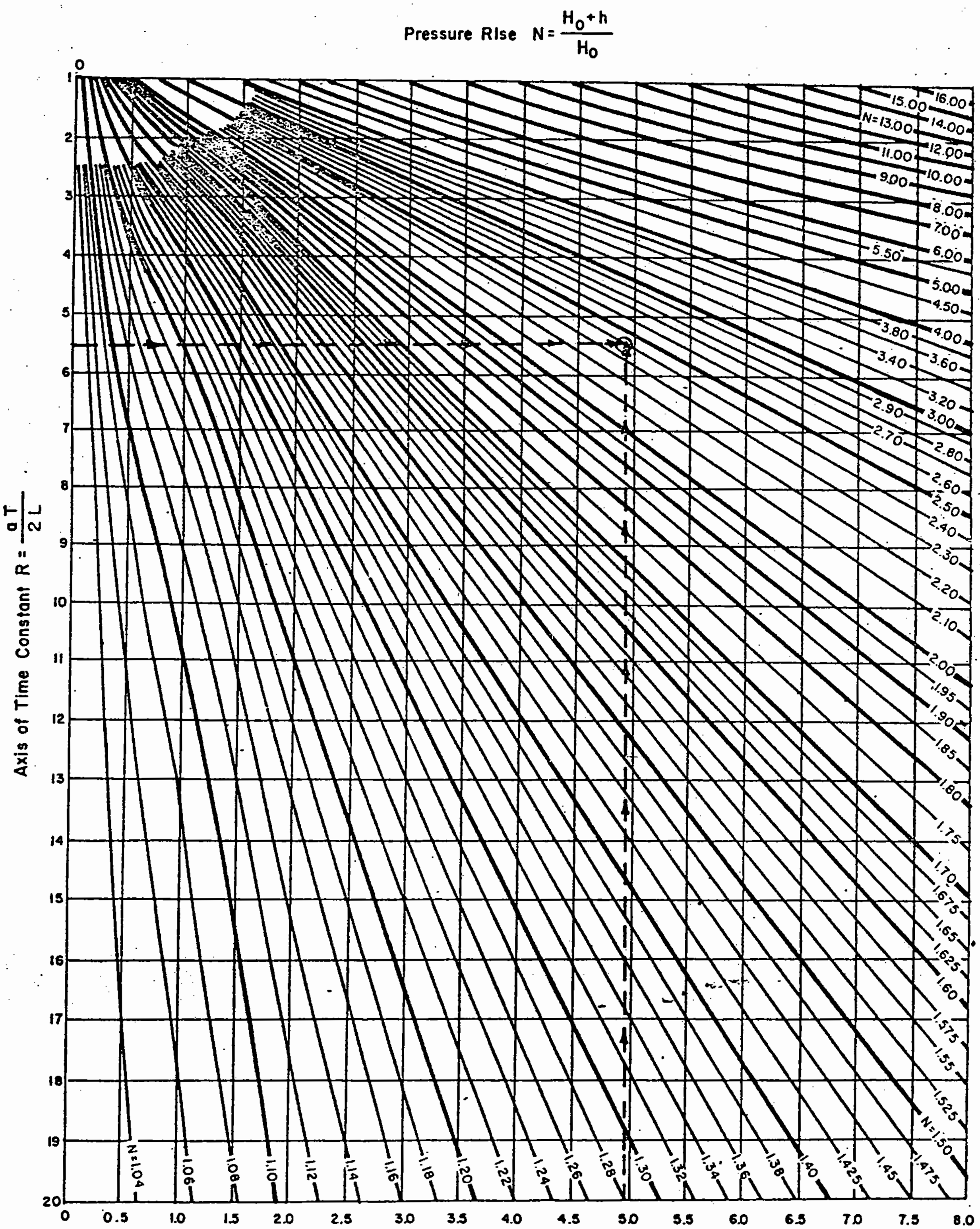
9. Calculator prints the Time constant, R = 7.01.

10. Using K and R found above, enter the Allievi Chart (Appendix 2) and find the percent pressure rise = 1.11.

11. Input percent pressure rise = 1.11, Press R/S.

12. Calculator prints pressure rise, in psi, HPSI = 7.15, and Total pressure on the pipe, HTOT = 72.15 psi.

This means that if the actual valve closure time is greater than 20 x 2 = 40 seconds, then pressures in the system should not exceed 72 psi.



Example :

Given: $a = 4{,}000$ fps ; $L = 2{,}000$ ft ; $T = 5.5$ sec.
$H_0 = 100$ ft; $V_0 = 8$ fps

Find: $R = 5.5$; $K = 4.96$ then $N = 2.4$; $h = 140$ ft

Reference : Engineering Topics 3 (AP)

FIGURE 13

EXCESS PRESSURES RESULTING FROM WATER HAMMER

PRELIMINARY DRAWING, SUBJECT TO REVIEW

USDA-SCS-PORTLAND, OREG. 1974

PLASTIC PIPE DIMENSIONS

Pipe Diameter And Type	PSI Rating PVC 1120 & 1220	O.D. Inches	I.D. Inches	Area Sq. Ft.
4" Nominal	--	--	4.00	0.0873
4" PIP Lowhead	22	4.13	4.00	0.0873
4" PIP	50	4.13	4.00	0.0873
4" PIP SDR 51	80	4.13	3.968	0.0859
4" PIP SDR 41	100	4.13	3.928	0.0842
4" PIP SDR 32.5	125	4.13	3.876	0.0819
4" IPS SDR 64	63	4.50	4.360	0.1037
4" IPS SDR 41	100	4.50	4.280	0.0999
4" IPS SDR 32.5	125	4.50	4.224	0.0973
4" IPS SDR 26	160	4.50	4.154	0.0941
4" IPS SDR 21	200	4.50	4.072	0.0904
5" Nominal	--	--	5.00	0.136
5" IPS SDR 64	63	5.563	5.389	0.158
5" IPS SDR 41	100	5.563	5.291	0.153
5" IPS SDR 32.5	125	5.563	5.221	0.149
5" IPS SDR 26	160	5.563	5.135	0.144
5" IPS SDR 21	200	5.563	5.033	0.138
6" Nominal	--	--	6.00	0.196
6" PIP Lowhead	22	6.14	6.00	0.196
6" PIP	50	6.14	5.988	0.195
6" PIP SDR 51	80	6.14	5.900	0.190
6" PIP SDR 41	100	6.14	5.840	0.186
6" PIP SDR 32.5	125	6.14	5.762	0.181
6" IPS SDR 64	63	6.625	6.417	0.225
6" IPS SDR 41	100	6.625	6.301	0.217
6" IPS SDR 32.5	125	6.625	6.217	0.211
6" IPS SDR 26	160	6.625	6.115	0.204
6" IPS SDR 21	200	6.625	5.993	0.196
8" Nominal	--	--	8.00	0.349
8" PIP Lowhead	22	8.16	8.00	0.349
8" PIP	50	8.16	7.958	0.345
8" PIP SDR 51	80	8.16	7.840	0.335
8" PIP SDR 41	100	8.16	7.762	0.329
8" PIP SDR 32.5	125	8.16	7.658	0.320
8" IPS SDR 64	63	8.625	8.355	0.381
8" IPS SDR 41	100	8.625	8.205	0.367
8" IPS SDR 32.5	125	8.625	8.095	0.357
8" IPS SDR 26	160	8.625	7.961	0.346
8" IPS SDR 21	200	8.625	7.805	0.332

(Cont.)

Pipe Diameter And Type	PSI Rating PVC 1120 & 1220	O.D. Inches	I.D. Inches	Area Sq. Ft.
10" Nominal	--	--	10.00	0.545
10" PIP Lowhead	22	10.20	10.00	0.545
10" PIP	50	10.20	9.948	0.540
10" PIP SDR 51	80	10.20	9.800	0.524
10" PIP SDR 41	100	10.20	9.702	0.513
10" PIP SDR 32.5	125	10.20	9.572	0.500
10" IPS SDR 64	63	10.750	10.414	0.592
10" IPS SDR 41	100	10.750	10.226	0.570
10" IPS SDR 32.5	125	10.750	10.088	0.555
10" IPS SDR 26.0	160	10.750	9.924	0.537
10" IPS SDR 21.0	200	10.750	9.728	0.516
12" Nominal	--	--	12.00	0.785
12" PIP Lowhead	22	12.24	12.00	0.785
12" PIP	50	12.24	11.938	0.777
12" PIP SDR 51	80	12.24	11.760	0.754
12" PIP SDR 41	100	12.24	11.642	0.739
12" PIP SDR 32.5	125	12.24	11.486	0.720
12" IPS SDR 64	63	12.750	12.352	0.832
12" IPS SDR 41	100	12.750	12.128	0.802
12" IPS SDR 32.5	125	12.750	11.966	0.781
12" IPS SDR 26.0	160	12.750	11.770	0.756
12" IPS SDR 21.0	200	12.750	11.538	0.726
14" Nominal	--	--	14.00	1.069
14" PIP Lowhead	22	14.28	14.00	1.069
14" PIP	50	14.28	13.928	1.058
14" PIP SDR 51	80	14.28	13.720	1.027
14" PIP SDR 41	100	14.28	13.584	1.006
14" PIP SDR 32.5	125	14.28	13.402	0.980
15" Nominal	--	--	15.00	1.23
15" PIP Lowhead	22	15.30	15.00	1.23
15" PIP	50	15.30	14.922	1.21
15" PIP SDR 51	80	15.30	14.700	1.18
15" PIP SDR 41	100	15.30	14.554	1.15
15" PIP SDR 32.5	125	15.30	14.358	1.12

Waterhammer Considerations for PVC Pipeline in Irrigation Systems

W. R. Seipt
MEMBER
ASAE

ABSTRACT

WATERHAMMER pressure develops whenever flow is changed. Flow changes occur by operating valves, by starting or stopping pumps, or by sudden release of entrapped air. Its intensity depends upon the rate of change. On occasion, it damages piping. Waterhammer can be contained by: adequate design; proper installation and responsible use.

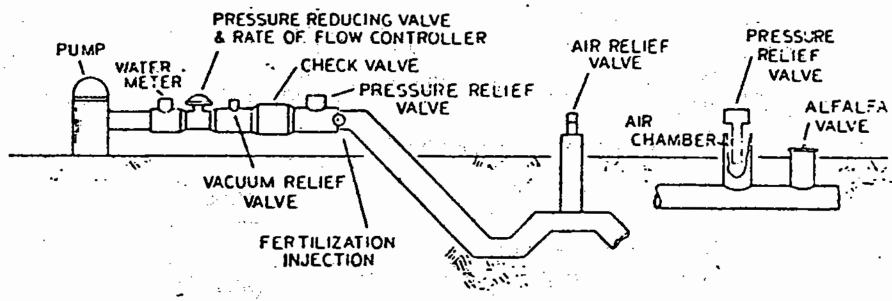


FIG. 1 Underground PVC piping irrigation system.

INTRODUCTION

A good irrigation system, providing satisfactory long term service, should have the lowest investment cost practical. An important part of any irrigation system is the underground piping to deliver the water from its source to the irrigation means (i.e. a sprinkler or the like), Fig. 1.

Poly (vinyl chloride), PVC, is an inexpensive piping material which, like any piping material, when adequately designed, properly engineered, properly installed, and responsibly used, will perform satisfactorily. The ways in which waterhammer is restrained to within acceptable bounds is a major consideration too often ignored.

One purpose of this paper is to draw attention to waterhammer, its causes, its extent and its effect. The second purpose is to emphasize the need to contain waterhammer forces through design, installation and use of an irrigation system.

Everyone has at one time or another experienced waterhammer. You hear it when a spigot is suddenly closed—pipes shake and simultaneously emit a sharp, hammer-like noise. Unbridled, waterhammer often does more than just vibrate and jar the piping; it imposes damage to the system—sometimes to a considerable extent, even to blowing pipe out of the ground, Fig. 2.

Article was submitted for publication in November 1973; reviewed and approved for publication by the Soil and Water Division of ASAE in January 1974. Presented as ASAE Paper No. 73-233.

The author is: W. R. SEIPT, Manager, Sales Engineering, Certain-teed Products Corp., Valley Forge, Pa.

BASIC CONSIDERATIONS

To understand waterhammer and its control, it is necessary to review the basic physical principle involved. Waterhammer occurs when water under pressure in a pipe line is subjected to a change in its rate of flow, (i.e. its velocity). The intensity of the waterhammer, evidenced as a surge in pressure, depends among other things upon the rapidity with which the velocity is altered.

Water flowing through a pipe bears energy. Part of this energy is kinetic, due to the velocity. Part is potential, a result of pressure. The sum of two energies (ignoring friction losses) remains constant throughout the line. Simply explained, whenever the velocity changes there follows a change in kinetic energy. Since the system does not essentially gain or lose energy, a compensating change occurs in potential energy with a corresponding change in pressure. Hence, when a valve is closed quickly and flow is brought to a rather sudden halt, relatively high pressures develop on the upstream side of the valve. This pressure-increase produces pressure-waves which travel the pipe and water system at sonic velocities—an effect designated waterhammer, see Figs. 3 and 4.

Since any change in water velocity produces a change in pressure, the velocity change should be made gradually so as to prevent excessive pressure increases.

CAUSES OF VARYING VELOCITY

Water velocity in a pipe of constant cross-sectional area will vary due to any one of the following conditions:

1. Closing a valve
2. Opening a valve
3. Rythmic valve operation
4. Starting a pump (especially a centrifugal pump, with or without a check valve in the pump discharge)
5. Stopping a pump
6. Pulsation of an operating reciprocating pump
7. Movement of air pockets along a pipe line
8. Sudden or rapid release of air from a pipe line
9. Sudden halt in flow when air has been exhausted out of an air release value
10. Recombination after water-column separation

INTENSITY OF WATERHAMMER PRESSURE

The increase of pressure in a pipeline full of flowing water due to a change in water velocity can be determined by the equation:

$$\Delta P = Ca\ (\Delta V)$$

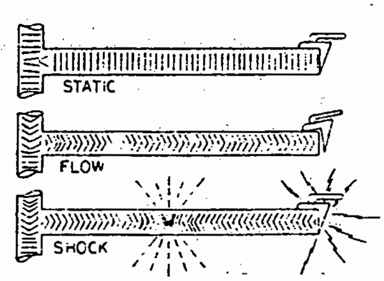


FIG. 2 Waterhammer generation.

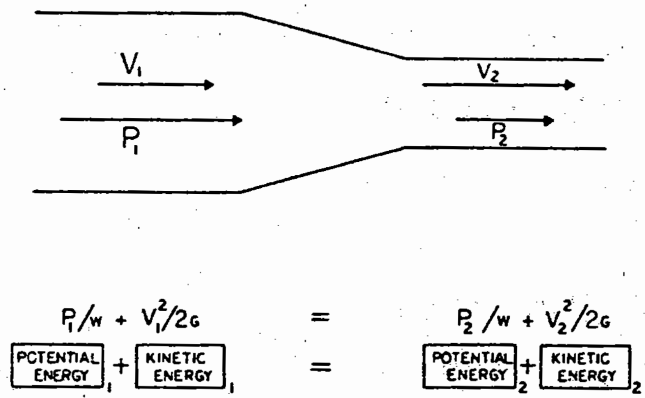


FIG. 3 Water flow energy adjustment.

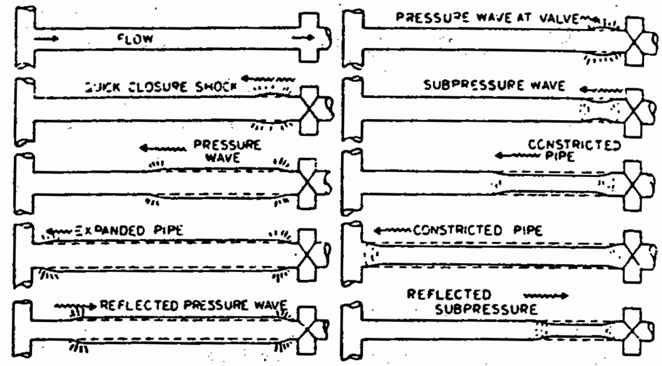


FIG. 4 Pressure wave propagation quick valve closure.

Where:

ΔP = pressure increase, psi
ΔV = velocity change, ft per sec
a = sonic velocity of pressure wave in pipe-water system, ft per sec
C = w/144g, a constant
w/144 = weight, lb per sq in. of a 1-ft column of water
g = acceleration of gravity, 32.2 ft per sec per sec

$$a = \frac{12}{\sqrt{\frac{w}{g}\left(\frac{1}{k} + \frac{C_1\, d}{Et}\right)}}$$

Where:

K = bulk modulus of water, 300,000 psi
E = modulus of elasticity of pipe material, 425,000 psi Type I PVC
d = pipe inside diameter, in.
t = pipe wall thickness, in.
C_1 = a factor dependent on pipe-end conditions and poisson ratio of the pipe material (anchored one end only for PVC $C_1 = 0.95$; anchored both ends but free at mid-length for PVC $C_1 = 0.85$)

$$SDR-2 = \frac{d}{t}$$

using $C_1 = 0.91$, for PVC type I

$$a = \frac{5892}{\sqrt{SDR-0.443}} \text{ and}$$

$$\Delta P = \frac{79.22\,\Delta V}{\sqrt{SDR-0.443}}$$

The pressure (class) rating of PVC Type I, Grade I is determined by

$$\overline{PR} = \frac{\frac{4000}{2}}{\frac{(SDR-1)}{2}}$$

Where:

$\overline{PR}$ = pressure (class) rating, psi $\frac{4000}{2}$ = design hoop stress, psi with a 2:1 safety factor

EFFECT OF VARYING VELOCITY

If we restrict waterhammer pressure to $\Delta P' = 0.2857\ \overline{PR}$ (based on a 2.8:1 safety factor) thereby allowing the remaining portion of the class rating, i.e. 0.7143 $\overline{PR}$ to represent the maximum operating pressures.

$$0.7143\ \overline{PR} = \frac{\left(\frac{4000}{2}\right)\left(\frac{2}{2.8}\right)}{\frac{(SDR-1)}{2}} = \frac{\left(\frac{4000}{2}\right)(0.7143)}{\frac{(SDR-1)}{2}}$$

Hence $\Delta P' = \frac{1143}{(SDR-1)} = \frac{79.22\ \Delta V'}{\sqrt{SDR-0.443}}$

From which $\Delta V' = \frac{14.43\ \sqrt{SDR-0.443}}{(SDR-1)}$

See Table 1.

Hence a sudden change in velocity of 2.92 ft per sec ($\Delta V' = 2.92$) will produce a maximum waterhammer pressure in an SDR 26 PVC pipe of

$$\Delta P = 15.67 \times \Delta V' = 15.67 \times 2.92 = 45.5 \text{ psi}$$

EFFECTS FROM AIR MOVEMENT

A very important factor affecting waterhammer pressures is that due to movement of air pockets. The seriousness of entrapped air is not generally realized nor understood. When an air pocket becomes suddenly dislodged, as by a stream of flowing water, the extent of changes in "local" fluid velocities and

TABLE 1. WAVE VELOCITY, WATERHAMMER, WATER VELOCITY CHANGE ~VS~ PVC SDR

SDR	$\overline{PR}$	a	P	$\Delta V'$
OD/wall ratio	Pressure rating, psi.	Surge velocity ft per sec	Waterhammer, psi per $\Delta V'$	Instant velocity change max, ft per sec
81	50	656	8.8	1.6
51	80	829	11.1	2.1
41	100	925	12.4	2.3
32.5	125	1040	14.0	2.6
26	160	1165	15.7	2.9
21	200	1300	17.5	3.3

$\overline{PR}$ = 4000/(SDR-1)
SDR = D/t = (d/t)+2
a = $5892/\sqrt{SDR-0.443}$
P = $79.22\ \Delta V/\sqrt{SDR-0.443}$
$\Delta V'$ = $14.43\sqrt{SDR-0.443}/SDR-1$

NOTE: The instantaneous velocity change produces P = 0.2857 x $\overline{PR}$

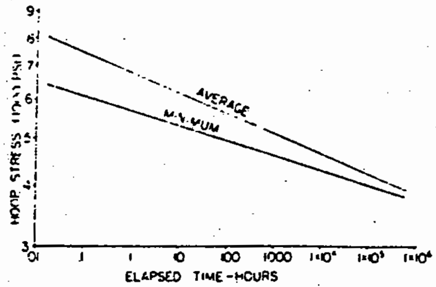


FIG. 5 PVC pipe, type I, grade I hoop stress regression (at 73.4 F).

the consequent waterhammer pressures are often much in excess of that accounted for by the general theory. Sometimes waterhammer pressures of several hundred psi or more are believed to develop. With PVC, as with any plastic piping, the effect of air entrapment is suspected to be more pronounced because air bubbles appear to "stick" more to plastic surfaces, hence the quantity of air entrapped at a particular point would be greater than that at surfaces of more wettable material. If such is the case, the larger quantity of air when finally dislodged would have the more devastating effect. For this reason, it is most important to rid PVC piping of air and to prevent air from getting into the system. Avoiding or getting rid of air is particularly difficult for an irrigation system because of the many times throughout the irrigation season the system is started and stopped.

WATERHAMMER DAMAGE

Unless steps are taken to restrict waterhammer pressures, damage may occur to one or many of the irrigation system elements, such as pumps, valves, or piping. Depending upon the intensity of the waterhammer pressure will determine the severity of the damage. Piping may suffer a hydrostatic burst, confined to the area of the waterhammer origin. More often, however, the pressure wave will propagate with little loss of intensity ahead of an ensuing burst propagation, thereby continuing to rend the pipe up to that point where it meets sufficient resistance to restrain its damaging force. Such a point of resistance may be at a joint. If the joint is of monolithic construction, i.e. one pipe length welded to the next or a pipe socket welded into an adjacent bell, the resistance to burst propagation is minimal and too frequently the damaging force will continue on through one or more such joints. Discontinuous joints, represented by rubber-gasketed seals, usually offer adequate resistance to stop a burst propagation. While gasketed joints do not remedy waterhammer damage, at least they generally reduce the extent of the damage considerably.

ADEQUATE DESIGN: PVC SAFETY FACTOR

A very misunderstood concept in PVC pipe design is its pressure (class) rating, and the safety factor attended thereto. The graph, Fig. 5, is a typical regression plot of PVC pipe, in which the ordinate is the log of pipe wall hoop stress in psi and the abscissa is the log of the time to failure, hour.

On this plot, when the stress is elevated to 6400 psi (3.2 times the class rating), the pipe will burst hydrostatically in 0.018 hr (65 sec) or longer. If pressured to a hoop stress of 4000 psi, burst will not occur before 100 000 hr. If, however, the pipe is stressed at 4000 psi for a period less than 100 000 hr, say 20 000 hr, it will still retain its original strength, i.e. it will burst at 6400 psi at or in excess of 65 sec.

Hence, the hydrostatic design basis has been established as 4000 psi. Then, by applying a 2:1 safety factor, the hydrostatic design stress is 2000 psi. Based upon the hoop stress formula, the pressure (class) rating of the pipe is determined from a hoop stress of 2000 psi.

$$\overline{PR} = \frac{\frac{4000}{2}}{\frac{(D-t)}{2t}} = \frac{4000}{(SDR-1)} \quad \text{(ISO Formula)}$$

Therefore after 10 years at the pressure rating, it can be said with certainty, and even after 100 years at the pressure rating it is reasonable to expect that PVC Type I, Grade I pipe will still retain all of its original strength.

Many manufacturers of PVC pipe advocate the use of a 2:1 safety factor, which means that they promote the use of their pipe at a maximum operating pressure equal to the pressure (class) rating of the pipe. No provisions are thereby made to allow for waterhammer pressures within the pressure (class) rating of the pipe. However, we at Certain-teed believe strongly that the maximum operating pressure *plus surge allowance* should not exceed the pressure (class) rating. Experience has taught that a 2:1 safety factor is not

TABLE 2. PVC MAXIMUM OPERATING PRESSURE FORMULA

$$\overline{MOP} = \frac{\overline{HDB/S.F.}}{(D-t)/2t} = \frac{4000/2.8}{(SDR-1)/2} = \frac{1430}{(SDR-1)/2} = \frac{2860}{SDR-1}$$

$\overline{MOP}$ = Max. operating pressure, psi.
HDB = Hydrostatic design basis, psi.
S.F. = Safety factor
D = Pipe outside dia., in.
t = Pipe wall thickness, in.
SDR = Std. Dimensional Ratio

adequate. For irrigation pipe, we recommend the maximum operating pressure not exceed 72 percent of the pressure (class) rating. This corresponds to a hoop stress of 1430 psi, or a safety factor of 2.8:1, see Table 2.

Hucks (1972) has shown that PVC exhibits also a cyclic stress regression curve, completely independent of the steady-state regression curve already discussed. Wilging(1972) in discussing Hucks' paper, graphically depicts the 2.8:1 safety factor, Fig. 6.

Using a 2.8:1 safety factor with a maximum hoop stress of 1430 psi plus a peak cyclic stress of 570 psi on top of that (a total of 2000 psi stress), the expected number of cycles to failure is 500 000. With an irrigation service life of 50 years, and a growing season of 80 days per year, this would allow 120 cycles per day, a factor probably 10 times that expected. Hence a 2.8:1 safety factor appears adequate.

In designing an irrigation system, it is important therefore to select pipe of an adequate pressure (class) rating. For example, if the maximum operating pressure is 90 psi, then a pipe of 125 psi rating (SDR 32.5) would be selected in order to provide a 2.8:1 safety factor.

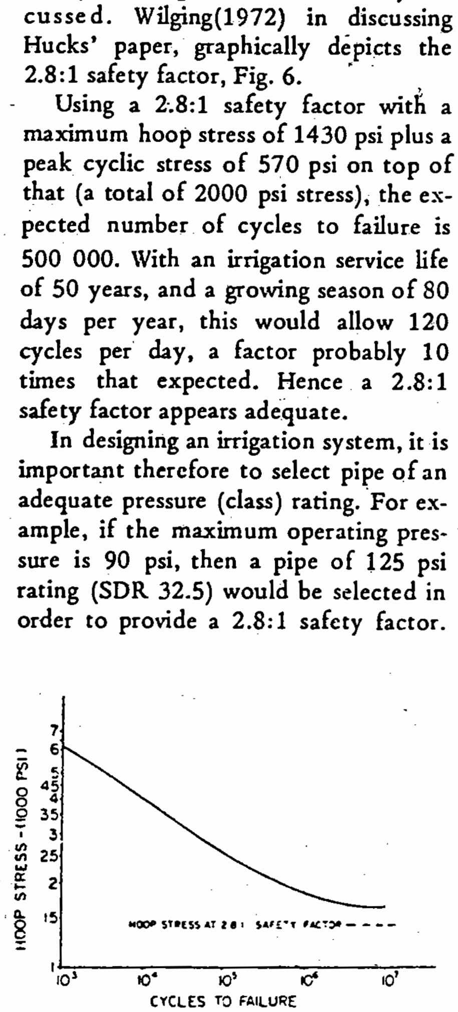


FIG. 6 PVC pipe, type I, grade I hoop stress versus cycle to failure.

TABLE 3. PVC MAXIMUM OPERATING PRESSURE ~VS~ SDR

SDR	$\overline{PR}$	$\overline{MOP}$
OD/wall ratio	Pressure (class) rating	Max. operating pressure psi
81	50	35
51	80	55
41	100	70
32.5	125	90
26	160	115
21	200	145

$SDR = D/t$

$\overline{PR} = \dfrac{4000}{SDR-1}$

$\overline{MOP} \doteq 0.71 \times PR$

$\doteq 2840/(SDR-1)$

D = Pipe outside diameter, in.
t = Pipe wall thickness, in.
SDR = Standard dimensional ratio
PR = Pressure (class) rating, psi.
MOP = Maximum operating pressure, psi.

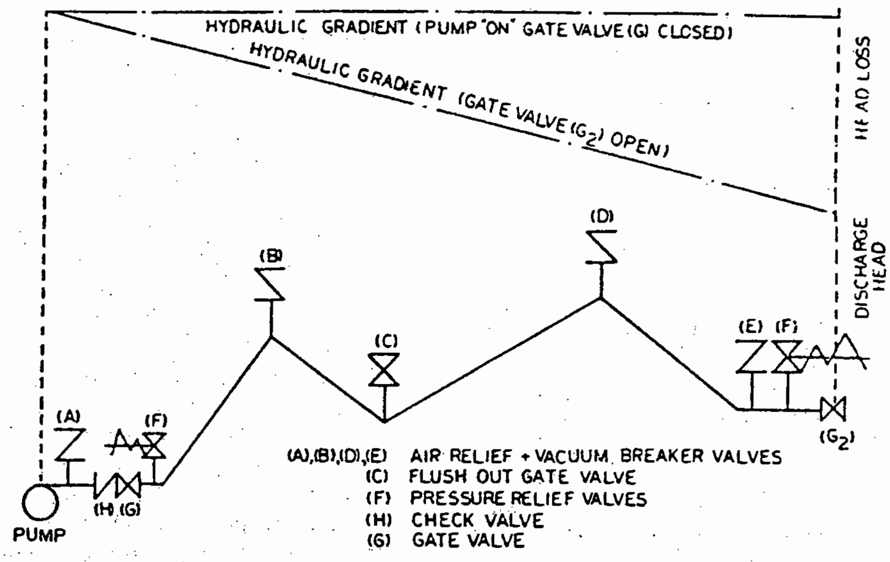


FIG. 7 Pipeline valving.

The Table 3 of maximum operating pressures, comply with the 2.8:1 safety factor:

Low head (50-ft) irrigation pipe should be used only for gravity flow systems, and should not have a valve in the discharge end of the line. Where a head gate or an entrance valve is used to stop or throttle flow, a vacuum-breaker valve should be installed immediately downstream from the entrance valve.

ADEQUATE DESIGN: VELOCITY AND PRESSURE

Waterhammer pressure due to closing a valve: the time required upon closing a valve for the pressure wave to travel from the valve to the pressure source and reflect back to the valve is given by the equation:

$$T_c = \frac{2L}{a}$$

Where

T_c = critical valve closure time, sec

L = Length of Line, ft

a = "sonic" velocity of pressure wave, ft per sec

The maximum waterhammer pressure will occur at the closed valve provided the time to complete valve closure is less than $\dfrac{2L}{a}$

The amount of waterhammer pressure, the pressure increase, is constant and maximum for valve closure times equal to or less than the critical time:

$$T \leq \frac{2L}{a}$$

Where:

T = valve closure time, sec

Since the maximum waterhammer pressure possible at the closed valve occurs when valve closure time does not exceed

$$\frac{2L}{a}$$

the critical time of valve closure which produces a maximum waterhammer pressure rise becomes of interest. As the following summary for PVC pipe shows, this close-time period increases with increasing length of pipe line.

The critical flow-stoppage time, T_c, in seconds yielding a maximum increase of waterhammer pressure at the valve is shown in Table 4 for various pipe SDR's and pipeline lengths:

By stopping flow at rates slower than critical time, waterhammer pressures will be reduced from their maximums. Charts and graphs are available to determine the time of flow-stoppage for various valve types and flow conditions which will provide acceptable waterhammer pressures (Kephert and Davis 1961, Kerr 1958). However, some indication of valve closure time to obtain a percentage of the maximum waterhammer pressure (force) $\dfrac{aV}{g}$

may be obtained by, first determining the pipe-line constant, P_c:

$$P_c = \left(\frac{aV}{2gPo}\right)\left(\frac{62.37}{144}\right) = \frac{aV}{148.8Po}$$

$$\text{\& Since } a = \frac{5892}{\sqrt{SDR-0.443}} \text{ for PVC}$$

$$P_c = \left(\frac{V}{Po}\right)\left(\frac{39.6}{\sqrt{SDR-0.443}}\right)$$

Where:

P_c = pipeline constant

a = "sonic" velocity of pressure wave, ft per sec

TABLE 4. CRITICAL FLOW STOPPAGE TIMES ~VS~ SDR

SDR	a	Tc = 2L/a, seconds		
OD/wall ratio	Surge velocity, ft per sec.	L=100 ft	L=1000 ft	L=10,000ft
81	656	0.31	3.05	30.5
51	829	0.24	2.41	24.1
41	925	0.22	2.16	21.6
32.5	1040	0.19	1.92	19.2
26	1165	0.17	1.72	17.2
21	1300	0.15	1.54	15.4

$a = 5892/\sqrt{SDR-0.443}$

SDR = Std. dimensional ratio
a = Surge velocity, ft per sec
Tc = Critical flow-stoppage time, sec
L = Pipeline length, ft

V = velocity of pipeline flow, ft per sec

P_o = pipeline pressure before valve closure, psi

g = acceleration of gravity, 32.2 ft per sec per sec

Generally when closing a valve, most of the flow is stopped between one-quarter and three-quarters of valve closure. Hence, actual valve closing time is twice that given by $T = \frac{2L}{a}$

Therefore, the actual valve closing time to produce critical flow-stoppage is approximately $T = \frac{4L}{a}$

sec. But to reduce the surge by four-fifths the maximum (i.e. to 20 percent of maximum) the above mentioned charts show that valve closure times must be increased by multiplying the critical flow-stoppage time, T_c, by the following factors, N:

When P_c	N
1	6.4
10	11.6

Hence, valve closing times should be those shown in Table 5.

Not only is it important in design, but in actual operation as well, to insure that value closing times be of the order of magnitude shown in Table 5. One means for ensuring safe waterhammer pressures is to limit the maximum velocity in the pipe line. Also shown in Table 5 (second column) are those velocities which will produce a maximum waterhammer pressure equal to 20 percent of the pipe's pressure (class) rating. Hence, we recommend that the design water velocity when operating at system capacity does not exceed 5 ft per sec, unless additional measures or ancillary equipment are used to ensure waterhammer pressures not in excess of 20 percent pipe's pressure (class) rating and that in no case should the velocity exceed 10 ft per sec.

ADEQUATE DESIGN: AIR RELIEF

Air trapped in a water line can, and often does, spell trouble. If trapped at the top of a rise, it can seriously impede flow.

Air is compressible and, if carried along a pipeline can act like a spring, being compressed at the bottom of a draw and expanding at the top of a rise. Such alternate compression and expansion produces velocity fluctuations and pressure variations which, if great enough, can produce serious waterhammer pressures.

Investigations of asbestos–cement pipelines have, for example, indicated that a sudden release of entrapped air can produce pressure increases which may be as much as 10 times the normal operating pressure of the lines. Similar magnitudes of pressure increase in PVC are believed also to occur—as witnessed when damaged pipelines were examined.

Water-column separation can also result in excessive waterhammer pressures when the separated column rejoins at high velocity. Furthermore, when the minimum pressure at any point in a line drops to the vapor pressure of water, the waterhammer solution is no longer valid. (Kephert and Davis 1961)

To prevent damage as a result of air entrapment during initial filling of a pipeline and to keep air from getting into the line from operating pumps, provisions should be made to remove air from the line at all high points. Combined air-relief and vacuum-breaker valves should be located at high points, (A), (B), (D), and (E) indicated in the diagram, Fig. 7.

A pressure-relief valve at (F) will limit waterhammer pressure which might result from too rapidly closing the gate valve—at the right end of the diagram. A flush valve (C) will help remove possible debris from the line's low point.

Reasons for locating the several combined air-relief and vacuum-breaker valves are as follows:

1 Air has a tendency to accumulate at crests and along the downstream side of the crest. Hence, several air vents should be located downstream of the crest and vented, through a manifold, into the air release valve located at the crest.

2 The valve at (A) is to eliminate air from a deep-well-pump column at startup and limits waterhammer at the check valve.

3 The valve at (B) is to eliminate air between the pump and (B) upon initial line-fill, to vent air accumulation with the system in operation under pressure and to avoid column separation if the pressure should drop below atmospheric.

4 The valve at (D) is to eliminate air between (C) and (D) and to avoid column separation.

5 The valve at (E) is to eliminate air between (D) and (E) and to avoid possible pipe collapse (in the case of thinner wall pipe, such as SDR 32.5 or higher (SDR) due to high water velocity which may exist going through the gate valve at the downstream end of the line. (Sturm 1970, Lescovich 1972).

In many instances, manually operated globe and gate valves have been installed on pipelines to eliminate air at high points. While cheaper than combined air-relief and vacuum-breaker valves, their use should be discouraged because they must be opened (and closed) manually. The automatic protection provided by the more sophisticated air-relief and vacuum-breaker valves is well worth their additional cost. Performance proves it.

If a line is laid in relatively flat terrain, provide at least three combined air-relief and vacuum-breaker valves. One should be in the pump discharge line ahead of the check and gate valves. A second should be near the middle of

TABLE 5. VALVE CLOSING TIMES ~VS~ SDR

SDR	V'	Valve closing time, T, seconds			
OD/wall ratio	Max. vel. change, ft per sec	L=1000 ft		L=10,000 ft	
		Pc=1	Pc=10	Pc=1	Pc=10
81	5.7	19.5	35.4	195	354
51	7.2	15.4	28.0	154	280
41	8.0	14.0	26.0	140	260
32.5	9.0	12.3	22.3	123	223
26	10.2	11.3	20.5	113	205
21	11.4	9.9	17.9	99	179

P_c	N
1	6.4
10	11.6

T = N(2L/a)

$P_c = (V/P_o)(39.6/\sqrt{SDR-0.443})$

$V' = 50.5\sqrt{SDR-0.443}/(SDR-1)$

P_c = Pipe line constant

P_o = Pressure in pipeline (before valve closure) psi.

V = Velocity in pipe line, ft per sec

V' = Max. velocity change producing waterhammer, $P=0.20\overline{PR}$, as by valve closure times shown the line and the third at the downstream end of the line. If several laterals take off from the main supply line, each one should have a combined air-relief and vacuum-breaker valve at its outermost end.

Everett (1967) points out that: "a popular misconception concerning waterhammer in a pumping system involves the relative gradient and system pressure. It is assumed that a low flat gradient and a low pressure will minimize the shock pressure. Conversely, a steep gradient and a high pressure on the system will produce an excessive shock pressure. This misconception should be reversed. Long flat lines with a small amount of gradient develop more shock pressure and are more susceptible to line failure than steep gradients at high pressure."

ADEQUATE DESIGN: PROTECTIVE EQUIPMENT

Many installations of PVC piping are supplied by motor-driven centrifugal pumps. These will be either horizontal-shaft pumps or vertical-shaft deep well turbine pumps, both driven by constant speed squirrel cage induction motors. In general, 1OHP and smaller will have full-voltage across-the-line starter units. Motors of greater horsepower will generally be provided with reduced-voltage starting. Hence, a pump-control of the flow in such cases is not possible. Flow control can be achieved by the opening or closing of a gate valve in the pump discharge, but must be done slowly and with due caution to the operating characteristics of the pump-drive system.

The designer of a PVC piping system supplied by the above mentioned pumping facilities, must consider the following features to ensure satisfactory performance:

1 Remove air from the line as it is being filled using automatic air-removal valves, properly sized and located at:
  (a) the pump discharge.
  (b) high points in the pipeline.
  (c) the downstream end of the pipeline.

2 Remove air from the riser pipe on deep well turbine pumps at start-up by a suitable air removal valve.

3 Provide pressure-relief valves at:
  (a) ahead of the gate valve in the pump discharge line.
  (b) at the downstream end of the pipe lines.

4 It may be necessary to install surge arrestors or automatic pressure reducing valves at:
  (a) flow regulators.
  (b) pump discharge.

5 It may be necessary to provide flow controllers so as to keep down the rate of filling and to reduce the start-up surge in a filled lined at:
  (a) pump discharge.
  (b) at downstream end of pipe line.

6 Always use a non-slam and preferably a controlled closing-rate check-valve at the pump discharge.

7 Besides protecting the pipe at pump start-up, provisions should be considered for reducing waterhammer at pump shut-down or at emergency shut-off as can occur from a power outage.

8 When shutting the system off, especially if it is to be started up again within several hours, the system should be designed, if possible, so as to keep out all air, then restart can begin with a completely, water-filled system.

9 Where the level of draw-down in the water supply can drop below that of the pump intake-line, air could be drawn in. This should be avoided and can be accomplished by the use of a pump-feed level-control.

10 The pump drive should operate at a relatively constant speed and not capable of suddenly racing to excessive speeds. A drive provided with throttled speed control is an advantage at start-up and at shut-off.

Check valves are used to protect the pump and drive from damage by a flow reversal and/or waterhammer. To protect the pipe line, use a non-slam check valve at a centrifugal-pump discharge so as to limit waterhammer pressure to a minimum. The check valve should close at the point of zero velocity, before the reflected surge wave returns from the downstream end. For even further protection, a surge-relief device (pressure-relief valve, surge chamber, etc.) should be located just downstream of the check valve.

Each type of irrigation system has its peculiarities of operating pressures and potential for surge which must be taken into account. Every system must be analyzed in the light of its own performance behavior and requirements, allowable water velocity, hydraulic gradient and pipeline profile (especially that leaving the pump discharge), pipe diameter, pipe wall thickness, and the needs for protective equipment selected to provide a satisfactory, economic system.

Where waterhammer pressures could develop with sufficient magnitude to damage PVC pipe, joining methods should be considered having one of the two following possibilities:

1 Use gasketed joints to confine the damage.

2 Where solvent-weld joints are used, install gasketed joints periodically to restrict the length of line damage should excessive waterhammer pressures develop.

While the use of air chambers can protect a line by limiting waterhammer pressures, they must be properly sized, correctly located and adequately maintained.

Pressure relief valves are actuated by a small increase in pressure above a pre-set value. They open to discharge water, thereby relieving pressure somewhat and restraining its build-up to a degree.

Since there are many appurtenances for pipeline protection and because of the varied flow conditions associated with a pipeline system, calculations to determine and control waterhammer can be complex. Analysis and treatment of the problem must be tempered with judgment and experience. This paper is concerned essentially with elementary elastic wave theory to determine the magnitude of waterhammer pressures. It is limited in its application to single lines of constant cross-section, containing valves and gates. The determination of waterhammer pressures and associated variations in lines supplied by pumps or supplying turbines cannot be adequately treated in a paper as limited in scope as this one.

An excellent treatment of valves used for surge control has been given in an article by Weaver (1972). Additional references are also given (Ref: Commercial Catalogues).

PROPER INSTALLATION

Properly installed pipe is a subject not to be ignored or overlooked, but will not be covered to any extent except to note that it should be done by accepted practices and in such a way as to permit safe operation. PVC pipe, like any piping material should be handled and treated with reasonable care. Rough handling, dropping the pipe, allowing it to strike or be struck by objects either before or after installation can seriously damage and weaken the pipe. Such impact damage, unfortunately, is not always apparent. If the pipe line gradient is steep, laying the pipe closer to grade will help to reduce the accumulation of air pockets. More detailed instruction in pipe line installation can be found in several references noted (SCS

432-D, SCS 432-E, ASTM D 2321, ASTM D 2774).

RESPONSIBLE USE

A very important factor in the responsible use of an irrigation system is proper system start-up. With an empty pipe line, fill as slowly as possible, observing the following cautions:

1 Never completely close the gate valve in the discharge of a deep well turbine type pump, because of the excessive shut-off head that develops.

2 Open all manual valves except in the pump discharge. Start filling the line slowly. It is suggested not to fill at a velocity in excess of 1 ft per sec. If it should be necessary to interrupt pumping while in the process of filling a pipe line, upon restart slow down the input rate even more (a velocity of 1/2 ft per sec maximum is recommended). When restarting into a partly filled line, the appraching steep water front (i.e. the approaching wall of water) may slam into the back of a stationary wall or into a more slowly moving water boundary with sufficient force to cause a rapid slow down of advancing water rate, particularly if air becomes entrapped between the fronts, and often results in damaging waterhammer pressures.

3 When water begins to discharge from the downstream end, there will most likely still be pockets of entrapped air. Continue to pump water through at a slow rate until no air is evident for at least a fifteen minute period. Then, if possible, shut off the pump while closing the system to keep air from getting in. Wait about 15 min before starting to pump again. Maintain the slow rate of flow until no air can be seen or heard at the discharge end for a least 15 min.

4 Close all manual valves slowly so as to increase the pressure slowly to the full operating line pressure, taking at least 10 min to do so. For larger diameter pipe (6 in. or larger), for longer lines (more than 1000 ft) and for the higher operating pressures (in excess of 100 psi) proportionately more than 10 min should be taken to bring the pressure up.

No valve should ever be closed in less than 10 sec (i.e. no less than 5 sec from one-quarter to three-quarters closed), preferably 30 sec or more would be a far safer valve-closure time.

Starting to pump into a filled line requires that velocity buildup and its attendant pressure rise be done gradually. The water should be started into the line slowly by either manual control or by automatic control and once assured that the line is free of air, the flow should be increased at a rate slow enough to limit waterhammer pressure.

Many times an irrigation system will be interrupted momentarily (i.e. shut off for a period of from 10 min to possibly several hours). It is just as important then to slow down flow as when slowly increasing flow at start-up. In so doing, close all valves to keep water in and to keep all air out. Then when restarting, it will not be necessary to repurge the line of air.

When stopping an irrigation system at any time for any reason, it is just as important that it be done with the same due care and caution as that for start-up. However, provisions should be made to assure protection from excessive waterhammer pressures, automatically at emergency shut-down (as by power outages, etc.). While such automatic means are protective, they generally do not reduce waterhammer pressure enough to be relied upon for repeated, routine shut-offs. In such cases, additional manual slow down or automatic throttling should be employed.

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TITLE FLEXIBLE PIPE EXTERNAL LOAD DESIGN PAGE 1 OF 2 Appendix 5

TI Programmable Program Record

PROGRAMMER Karl Larson DATE March 1982

Partitioning (Op 17) 4 7 9 5 9 Library Module No Printer Yes Cards 2 sides

PROGRAM DESCRIPTION

This program finds the vertical deflection of a flexible pipe, based on the magnitude of the live load applied at ground surface and the dead load of the soil on the pipe. The Modified Iowa Equation is used to find the vertical deflection in the pipe.

$$\Delta Y = 1.1 \Delta X = \frac{D_L(K)(WC)r^3 \, 1.1}{EI + .061(E')r^3} \quad \text{where } WC = \frac{WDP + WL}{12} \quad \text{and } D_L = 1.5 \quad \text{and } K = 0.10$$

$$\text{and } WL = \frac{0.48(P)(BC)}{H^2} \qquad \text{and } WDP = H(w)(BC)$$

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS		DISPLAY
1.	Insert Mag Card 2 sides	1, 2			1., 2.
2.	Input height of fill over pipe, in feet		B		Prints H
3.	Input outside pipe diameter, in feet		C		Prints BC
4.	Input soil unit weight, in pounds per cubic foot		D		Prints UNWT
5.	Input concentrated live load at ground surface, inpounds		E		Prints P
6.	Input Modulus of Soil Reaction, in psi		2nd	A	Prints E'
	(See Table on Sheet 2)				
7.	Input Modulus of Tensile Elasticity of pipe, in psi		2nd	B	Prints E
	a. PVC E = 400,000 psi				
	b. Steel E = 29,000,000 psi				
8.	Input wall thickness of pipe, in inches		2nd	C	Prints T
9.	Input impact factor for live load		2nd	D	Prints IF
	a. Select value between 1.1 and 1.5 for soil cover less than 4 feet over pipe				
	b. Select value of 1.0 for depths greater than 4 feet.				
10.	To begin Calculations and to print out the following:		A		
	a. Live Load (WL) at pipe depth, in #/lin. ft.				Prints WL
	b. Dead Load (WDP) at pipe depth, in #/lin. ft.				Prints WDP
	c. Total load (WC) at pipe depth, in #/lin. inch				Prints WC
	d. Amount of vertical deflection in inches				Prints DEFL
	e. Amount of vertical deflection, in percent of diameter				Prints %DFL

USER DEFINED KEYS	DATA REGISTERS (INV List)		LABELS (Op 08)
A	0	0	INV lnx CE CLR x⇄t x²
B	1	1	√x 1/x STO RCL SUM y^x
C	2	2	EE ( ) ÷ GTO ×
D	3	3	SBR − RST + R/S .
E	4	4	+/− =
A'	5	5	
B'	6	6	
C'	7	7	
D'	8	8	
E'	9	9	

FLAGS 0 1 2 3 4 5 6 7 8 9

TITLE FLEXIBLE PIPE EXTERNAL LOAD DESIGN PAGE 1 OF 2

PROGRAMMER Karl Larson DATE March 1982

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS
000	76	LBL	
001	12	B	
002	42	STO	
003	01	01	
004	02	2	
005	03	3	
006	69	OP	
007	04	04	
008	43	RCL	
009	01	01	
010	69	OP	
011	06	06	
012	91	R/S	
013	76	LBL	
014	13	C	
015	42	STO	
016	02	02	
017	01	1	
018	04	4	
019	01	1	
020	05	5	
021	69	OP	
022	04	04	
023	43	RCL	
024	02	02	
025	69	OP	
026	06	06	
027	91	R/S	
028	76	LBL	
029	14	D	
030	42	STO	
031	03	03	
032	04	4	
033	01	1	
034	03	3	
035	01	1	
036	04	4	
037	03	3	
038	03	3	
039	07	7	
040	69	OP	
041	04	04	
042	43	RCL	
043	03	03	
044	69	OP	
045	06	06	
046	91	R/S	
047	76	LBL	
048	15	E	
049	42	STO	
050	04	04	
051	03	3	
052	03	3	
053	69	OP	

LOC	CODE	KEY	COMMENTS
055	43	RCL	
056	04	04	
057	69	OP	
058	06	06	
059	91	R/S	
060	76	LBL	
061	16	A'	
062	42	STO	
063	05	05	
064	01	1	
065	07	7	
066	06	6	
067	05	5	
068	69	OP	
069	04	04	
070	43	RCL	
071	05	05	
072	69	OP	
073	06	06	
074	91	R/S	
075	76	LBL	
076	17	B'	
077	42	STO	
078	06	06	
079	01	1	
080	07	7	
081	69	OP	
082	04	04	
083	43	RCL	
084	06	06	
085	69	OP	
086	06	06	
087	91	R/S	
088	76	LBL	
089	18	C'	
090	42	STO	
091	07	07	
092	03	3	
093	07	7	
094	69	OP	
095	04	04	
096	43	RCL	
097	07	07	
098	69	OP	
099	06	06	
100	91	R/S	
101	76	LBL	
102	19	D'	
103	42	STO	
104	08	08	
105	02	2	
106	04	4	
107	02	2	
108	01	1	
109	69	OP	

LOC	CODE	KEY	COMMENTS
110	04	04	
111	43	RCL	
112	08	08	
113	69	OP	
114	06	06	
115	91	R/S	
116	76	LBL	
117	11	A	
118	43	RCL	
119	04	04	
120	65	x	
121	43	RCL	
122	02	02	
123	65	x	
124	93	.	
125	04	4	
126	08	8	
127	55	÷	
128	43	RCL	
129	01	01	
130	33	X^2	
131	95	=	
132	65	x	
133	43	RCL	
134	08	08	
135	95	=	
136	42	STO	
137	09	09	
138	04	4	
139	03	3	
140	02	2	
141	07	7	
142	69	OP	
143	04	04	
144	43	RCL	
145	09	09	
146	69	OP	
147	06	06	
148	43	RCL	
149	01	01	
150	65	x	
151	43	RCL	
152	03	03	
153	65	x	
154	43	RCL	
155	02	02	
156	95	=	
157	42	STO	
158	10	10	
159	04	4	

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

TEXAS INSTRUMENTS INCORPORATED

TITLE EXTERNAL LOAD DESIGN PAGE 2 OF 2 TI Programmable Program Record

PROGRAMMER Karl Larson DATE March 1982

Partitioning (Op 17) 4,7,9,5,9 Library Module No Printer Yes Cards 2 Sides

AVERAGE VALUES OF MODULUS OF SOIL REACTION, E′
(For Initial Flexible Pipe Deflection)

Soil type-pipe bedding material (Unified Classification System[a]) (1)	E′ for Degree of Compaction of Bedding, in pounds per square inch: Dumped (2)	Slight, <85% Proctor, <40% relative density (3)	Moderate, 85%–95% Proctor, 40%–70% relative density (4)	High, >95% Proctor, >70% relative density (5)
Fine-grained Soils (LL > 50)[b] Soils with medium to high plasticity CH, MH, CH-MH	No data available: consult a competent soils engineer; Otherwise use E′ = 0			
Fine-grained Soils (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with less than 25% coarse-grained particles	50	200	400	1,000
Fine-grained Soils (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with more than 25% coarse-grained particles; Coarse-grained Soils with Fines GM, GC, SM, SC[c] contains more than 12% fines	100	400	1,000	2,000
Coarse-grained Soils with Little or No Fines GW, GP, SW, SP[c] contains less than 12% fines	200	1,000	2,000	3,000
Crushed Rock	1,000	3,000	3,000	3,000
Accuracy in Terms of Percentage Deflection[d]	±2	±2	±1	±0.5

[a]ASTM Designation D-2487, USBR Designation E-3.
[b]LL = Liquid limit.
[c]Or any borderline soil beginning with one of these symbols (i.e., GM-GC, GC-SC).
[d]For ±1% accuracy and predicted deflection of 3%, actual deflection would be between 2% and 4%.

Note: Values applicable only for fills less than 50 ft (15 m). Table does not include any safety factor. For use in predicting initial deflections only, appropriate Deflection Lag Factor must be applied for long-term deflections. If bedding falls on the borderline between two compaction categories, select lower E′ value or average the two values. Percentage Proctor based on laboratory maximum dry density from test standards using about 12,500 ft-lb/cu ft (598,000 J/m³) (ASTM D-698, AASHO T-99, USBR Designation E-11). 1 psi = 6.9 kN/m².

STEP ... ESS ... DISPLAY

TYPICAL OUTPUT

4.	H
1.	BC
120.	UNWT
10000.	P
700.	E'
400000.	E
0.299	T
1.2	IF
360.	WL
480.	WDP
70.	WC
.2466623765	DEFL
2.055519804	%DFL

USER DEFINED KEYS
A
B
C
D
E
A'
B'
C'
D'
E'

LABELS (Op 08)

INV lnx CE CLR x⇄t x²
√x 1/x STO RCL SUM yˣ
EE ( ) ÷ GTO ×
SBR − RST + R/S .
+/− =

FLAGS 0 1 5 6 7 8 9

TITLE FLEXIBLE PIPE EXTERNAL LOAD DESIGN PAGE 2 OF 2

PROGRAMMER Karl Larson DATE March 1982

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS
160	03	3	
161	01	1	
162	06	6	
163	03	3	
164	03	3	
165	69	OP	
166	04	04	
167	43	RCL	
168	10	10	
169	69	OP	
170	06	06	
171	85	+	
172	43	RCL	
173	09	09	
174	95	=	
175	55	÷	
176	01	1	
177	02	2	
178	95	=	
179	42	STO	
180	11	11	
181	04	4	
182	03	3	
183	01	1	
184	05	5	
185	69	OP	
186	04	04	
187	43	RCL	
188	11	11	
189	69	OP	
190	06	06	
191	43	RCL	
192	07	07	
193	45	YX	
194	03	3	
195	95	=	
196	55	÷	
197	01	1	
198	02	2	
199	95	=	
200	65	×	
201	43	RCL	
202	06	06	
203	95	=	
204	42	STO	
205	12	12	
206	43	RCL	
207	02	02	
208	65	×	
209	06	6	
210	95	=	
211	45	YX	
212	03	3	
213	95	=	
214	42	STO	
215	13	13	
216	65	×	
217	43	RCL	
218	05	05	
219	65	×	
220	93	.	
221	00	0	
222	06	6	
223	01	1	
224	95	=	
225	85	+	
226	43	RCL	
227	12	12	
228	95	=	
229	35	1/X	
230	65	×	
231	43	RCL	
232	13	13	
233	65	×	
234	43	RCL	
235	11	11	
236	65	×	
237	93	.	
238	01	1	
239	65	×	
240	01	1	
241	93	.	
242	05	5	
243	65	×	
244	01	1	
245	93	.	
246	01	1	
247	95	=	
248	42	STO	
249	14	14	
250	01	1	
251	06	6	
252	01	1	
253	07	7	
254	02	2	
255	01	1	
256	02	2	
257	07	7	
258	69	OP	
259	04	04	
260	43	RCL	
261	14	14	
262	69	OP	
263	06	06	
264	55	÷	
265	43	RCL	
266	02	02	
267	55	÷	
268	01	1	
269	02	2	
270	65	×	
271	01	1	
272	00	0	
273	00	0	
274	95	=	
275	42	STO	
276	15	15	
277	06	6	
278	01	1	
279	01	1	
280	06	6	
281	02	2	
282	01	1	
283	02	2	
284	07	7	
285	69	OP	
286	04	04	
287	43	RCL	
288	15	15	
289	69	OP	
290	06	06	
291	98	ADV	
292	91	R/S	

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

COMPUTATION SHEET
SCS-ENG-523 Rev. 8-69

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

STATE Idaho		PROJECT All Jobs		
BY KDL	DATE 4/2/82	CHECKED BY	DATE	JOB NO.
SUBJECT External Load Design				SHEET 1 OF 1

EXAMPLE PROBLEM

Given: Height of Fill over Pipe = 4 feet.
Outside Diameter of Pipe = 1 foot.
Unit Weight of Soil over Pipe = 120#/ft^3.
Live Load of Ground Surface = 10,000#.
Modulus of Soil Reaction = 700 psi.
Modulus of Elasticity of Pipe = 400,000 psi.
Wall Thickness of Pipe = 0.299 inches.
Impact Factor for Live Load = 1.2.

Procedure

1. Input the given values in accordance with instructions in Appendix 5.

2. Press A.

3. Calculator prints out:

   a. Live Load = 360#/lin.ft.

   b. Dead Load = 480#/lin.ft.

   c. Total Load = 70#/lin. inch.

   d. Vertical Deflection = 0.25 inches.

   e. Vertical Deflection = 2.055% of Pipe Diameter.

PIPELINE DESIGN

Appendix 6

TITLE GENERAL WATERHAMMER ANALYSIS PAGE 4 OF 4

TI Programmable Program Record

PROGRAMMER West NTC/ Larson DATE Jan 1983

Partitioning (Op 17) 6 3 9 3 9 Library Module No Printer PC100 C Cards 3 Banks

PROGRAM DESCRIPTION

MODULUS OF ELASTICITY FOR SOME COMMON PIPING MATERIALS

Asbestos-Cement	3,000,000 psi
Cast Iron	15,000,000
Ductile Iron	24,000,000
PVC	400,000
Polyethylene	100,000
Steel	30,000,000

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY

USER DEFINED KEYS: A, B, C, D, E, A', B', C', D', E'

DATA REGISTERS (INV Int): 0–9, 0–9

LABELS (Op 08)

FLAGS 0 1 2 3 4 5 6 7 8 9

TITLE GENERAL WATERHAMMER ANALYSIS PAGE 4 OF 4

TI Programmable Coding Form

PROGRAMMER ______ DATE ______

LOC	CODE	KEY	COMMENTS
480	42	STO	
481	17	17	
482	43	RCL	
483	36	36	
484	69	OP	
485	04	04	
486	43	RCL	
487	17	17	
488	69	OP	
489	06	06	
490	43	RCL	
491	18	18	
492	32	X:T	
493	25	CLR	
494	43	RCL	
495	17	17	
496	85	+	
497	02	2	
498	95	=	
499	77	GE	
500	34	√X	
501	43	RCL	
502	36	36	
503	69	OP	
504	04	04	
505	43	RCL	
506	18	18	
507	69	OP	
508	06	06	
509	43	RCL	
510	18	18	
511	85	+	
512	43	RCL	
513	06	06	
514	95	=	
515	42	STO	
516	08	08	
517	98	ADV	
518	03	3	
519	00	0	
520	01	1	
521	03	3	
522	04	4	
523	04	4	
524	00	0	
525	00	0	
526	03	3	
527	07	7	
528	69	OP	
529	01	01	
530	03	3	
531	02	2	
532	03	3	
533	07	7	
534	[illegible]	[illegible]	

LOC	CODE	KEY	COMMENTS
535	03	3	
536	02	2	
537	07	7	
538	00	0	
539	00	0	
540	69	OP	
541	02	02	
542	02	2	
543	03	3	
544	01	1	
545	07	7	
546	01	1	
547	03	3	
548	01	1	
549	06	6	
550	00	0	
551	00	0	
552	69	OP	
553	03	03	
554	06	6	
555	04	4	
556	00	0	
557	00	0	
558	00	0	
559	00	0	
560	69	OP	
561	04	04	
562	69	OP	
563	05	05	
564	02	2	
565	03	3	
566	04	4	
567	07	7	
568	02	2	
569	03	3	
570	03	3	
571	02	2	
572	69	OP	
573	04	04	
574	43	RCL	
575	08	08	
576	69	OP	
577	06	06	
578	91	R/S	
579	76	LBL	
580	34	√X	
581	43	RCL	
582	23	23	
583	55	÷	
584	43	RCL	
585	32	32	
586	95	=	
587	42	STO	
588	30	30	
589	[illegible]	[illegible]	

LOC	CODE	KEY	COMMENTS

MERGED CODES

62 Pgm Ind 72 STO Ind 83 GTO Ind
63 Exc Ind 73 RCL Ind 84 Op Ind
64 Prd Ind 74 SUM Ind 92 INV SBR

TEXAS INSTRUMENTS INCORPORATED

Appendix 6

TITLE PIPELINE DESIGN GENERAL WATERHAMMER ANALYSIS PAGE 3 OF 4

PROGRAMMER West NTC/ Larson DATE Jan 1983

TI Programmable Program Record

Partitioning (Op 17) Library Module Printer Cards

PROGRAM DESCRIPTION

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS	DISPLAY
	Labels Used			

001	11	A
033	12	B
046	13	C
061	14	D
074	16	A'
089	17	B'
102	18	C'
157	15	E
290	45	YX
326	44	SUM
331	35	1/X
380	32	TX

USER DEFINED KEYS	DATA REGISTERS (INV Ind)		LABELS (Op 08)
A	0	0	INV lnx CE CLR x⇌t x²
B	1	1	√x 1/x STO RCL SUM yˣ
C	2	2	EE ( ) ÷ GTO ×
D	3	3	SBR − RST + R/S .
E	4	4	+/− =
A'	5	5	
B'	6	6	
C'	7	7	
D'	8	8	
E'	9	9	

TITLE GENERAL WATERHAMMER ANALYSIS PAGE 3 OF 4

TI Programmable Coding Form

PROGRAMMER ______ DATE ______

LOC	CODE	KEY	COMMENTS
320	22	INV	
321	77	GE	
322	44	SUM	
323	61	GTO	
324	35	1/X	
325	76	LBL	
326	44	SUM	
327	00	0	
328	42	STO	
329	29	29	
330	76	LBL	
331	35	1/X	
332	43	RCL	
333	24	24	
334	69	OP	
335	04	04	
336	43	RCL	
337	29	29	
338	69	OP	
339	06	06	
340	43	RCL	
341	29	29	
342	55	÷	
343	43	RCL	Prts A
344	31	31	
345	65	×	
346	43	RCL	
347	27	27	
348	34	√X	
349	95	=	
350	42	STO	
351	26	26	
352	43	RCL	
353	15	15	
354	94	+/-	
355	42	STO	
356	12	12	
357	53	(	
358	43	RCL	
359	33	33	
360	65	×	
361	43	RCL	
362	26	26	
363	33	X²	
364	55	÷	
365	43	RCL	
366	27	27	
367	54	)	
368	94	+/-	
369	85	+	
370	43	RCL	
371	26	26	
372	55	÷	
373	02	2	
374	65	×	

LOC	CODE	KEY	COMMENTS
375	53	(	
376	53	(	
377	43	RCL	
378	33	33	
379	65	×	
380	43	RCL	
381	26	26	
382	55	÷	
383	43	RCL	
384	28	28	
385	54	)	
386	33	X²	
387	85	+	
388	04	4	
389	65	×	
390	53	(	
391	43	RCL	
392	06	06	
393	85	+	
394	43	RCL	
395	33	33	
396	65	×	
397	43	RCL	
398	02	02	
399	55	÷	
400	43	RCL	
401	28	28	
402	85	+	
403	02	2	
404	65	×	
405	43	RCL	
406	12	12	
407	54	)	
408	54	)	
409	50	|X|	
410	34	√X	
411	95	=	
412	42	STO	
413	13	13	
414	04	4	
415	02	2	
416	42	STO	
417	37	37	
418	69	OP	
419	04	04	
420	43	RCL	
421	13	13	
422	69	OP	
423	06	06	
424	53	(	
425	43	RCL	
426	33	33	
427	55	÷	Prts V
428	43	RCL	

LOC	CODE	KEY	COMMENTS
430	54	)	
431	94	+/-	
432	65	×	
433	53	(	
434	43	RCL	
435	13	13	
436	75	-	
437	43	RCL	
438	02	02	
439	54	)	
440	85	+	
441	43	RCL	
442	12	12	
443	95	=	
444	42	STO	
445	14	14	
446	43	RCL	
447	34	34	
448	69	OP	
449	04	04	
450	43	RCL	
451	14	14	
452	69	OP	
453	06	06	
454	43	RCL	
455	17	17	
456	42	STO	
457	18	18	Prts F+
458	43	RCL	
459	35	35	
460	69	OP	
461	04	04	
462	43	RCL	
463	12	12	
464	69	OP	
465	06	06	
466	43	RCL	
467	16	16	
468	42	STO	
469	15	15	Prts F-
470	43	RCL	
471	14	14	
472	42	STO	
473	16	16	
474	43	RCL	
475	14	14	
476	85	+	
477	43	RCL	
478	12	12	
479	95	=	

MERGED CODES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

PIPELINE DESIGN

TITLE GENERAL WATER HAMMER ANALYSIS Appendix 6 PAGE 2 OF 4

TI Programmable Program Record

PROGRAMMER West NTC/ Larson DATE Jan 1983

Partitioning (Op 17) 6,3,9,3,9 Library Module No Printer PC100C Cards 3 banks

PROGRAM DESCRIPTION

NOTES: This program will find the peak pressures whether the valve is closed in less time than the critical time or not. All outputs are pressures at the valve. The program will not evaluate varying pipe sizes. Principal reference for this program is "Waterhammer Analysis" by John Parmakian and the Uni-Bell Plastic Pipe Association.

Valve closure time (TC) is defined as about 50% of the actual closing time of most valves.

USER INSTRUCTIONS

Input Data		Trial 2		Trial 3	
24.	ID				
0.685	T				
4.3	VO				
6730.	L				
5.	TC				
400000.	E				
205.	HD	20.	TC	30.	TC
Output					
14.16150135	2L/A	14.16150135	2L/A	14.16150135	2L/A
0.	TIME	0.	TIME	0.	TIME
.1175705268	A	.1175705268	A	.1175705268	A
4.3	V	4.3	V	4.3	V
.0000000005	F+	.0000000005	F+	.0000000005	F+
0.	F-	0.	F-	0.	F-
.0000000005	H+	.0000000005	H+	.0000000005	H+
7.080750677	TIME	7.080750677	TIME	7.080750677	TIME
0.	A	.0759461474	A	.0898209405	A
0.	V	3.022353687	V	3.474784695	V
126.925343	F+	37.71295266	F+	24.35831062	F+
0.	F-	0.	F-	0.	F-
126.925343	H+	37.71295266	H+	24.35831062	H+
14.16150135	TIME	14.16150135	TIME	14.16150135	TIME
0.	A	.0343217681	A	.0620713543	A
0.	V	1.487867865	V	2.541406893	V
126.925343	F+	83.00717109	F+	51.90931005	F+
-.0000000005	F-	-.0000000005	F-	-.0000000005	F-
126.925343	H+	83.00717109	H+	51.90931005	H+
21.24225203	TIME	21.24225203	TIME	21.24225203	TIME
0.	A	0.	A	.0343217681	A
0.	V	0.	V	1.366333601	V
0.	F+	99.21239031	F+	62.23625073	F+
-126.925343	F-	-37.71295266	F-	-24.35831062	F-
-126.925343	H+	51.49943765	H+	37.87794011	H+
126.925343	H+	83.00717109	H+	51.90931005	H+
MAX TOTAL HEAD =		MAX TOTAL HEAD =		MAX TOTAL HEAD =	
331.925343	H+HD	288.0071711	H+HD	256.90931	H+HD

Appendix 6

TITLE GENERAL WATERHAMMER ANALYSIS PAGE 2 OF 4

TI Programmable Coding Form

PROGRAMMER DATE

LOC	CODE	KEY	COMMENTS
160	55	÷	
161	53	(	
162	43	RCL	
163	06	06	
164	65	x	
165	43	RCL	
166	27	27	
167	54	)	
168	34	√X	
169	65	x	
170	43	RCL	
171	31	31	
172	95	=	
173	42	STO	
174	29	29	
175	42	STO	
176	23	23	
177	01	1	
178	03	3	
179	42	STO	
180	24	24	
181	98	ADV	
182	00	0	
183	42	STO	
184	12	12	
185	42	STO	
186	15	15	
187	42	STO	
188	18	18	
189	42	STO	
190	16	16	
191	42	STO	
192	30	30	
193	42	STO	
194	17	17	
195	43	RCL	
196	23	23	
197	42	STO	
198	29	29	
199	43	RCL	
200	00	00	
201	65	x	
202	93	.	
203	09	9	
204	55	÷	
205	43	RCL	
206	01	01	
207	55	÷	
208	43	RCL	
209	05	05	
210	95	=	
211	85	+	
212	53	(	
213	01	1	
214	55	÷	

LOC	CODE	KEY	COMMENTS
215	03	3	
216	00	0	
217	00	0	
218	00	0	
219	00	0	
220	00	0	
221	54	)	
222	95	=	
223	65	x	
224	01	1	
225	93	.	
226	09	9	
227	04	4	
228	95	=	
229	34	√X	
230	35	1/X	
231	65	x	
232	01	1	
233	02	2	
234	95	=	
235	42	STO	
236	33	33	
237	43	RCL	
238	04	04	
239	55	÷	
240	53	(	
241	43	RCL	
242	03	03	
243	55	÷	
244	43	RCL	
245	33	33	
246	54	)	
247	95	=	
248	42	STO	
249	32	32	
250	02	2	
251	65	x	
252	43	RCL	
253	03	03	
254	55	÷	
255	43	RCL	
256	33	33	
257	95	=	
258	42	STO	
259	07	07	
260	00	0	
261	03	3	
262	02	2	
263	07	7	
264	06	6	
265	03	3	
266	01	1	
267	03	3	
268	69	OP	
269	04	04	

LOC	CODE	KEY	COMMENTS
270	43	RCL	
271	07	07	
272	69	OP	
273	06	06	
274	43	RCL	
275	03	03	
276	55	÷	
277	43	RCL	
278	33	33	
279	95	=	
280	42	STO	
281	20	20	
282	00	0	
283	75	-	
284	43	RCL	
285	20	20	
286	95	=	
287	42	STO	
288	21	21	
289	76	LBL	
290	45	YX	
291	98	ADV	
292	69	OP	
293	00	00	
294	43	RCL	
295	22	22	
296	69	OP	
297	04	04	
298	43	RCL	
299	21	21	
300	85	+	
301	43	RCL	
302	20	20	
303	95	=	
304	42	STO	
305	21	21	
306	69	OP	
307	06	06	
308	43	RCL	
309	29	29	
310	75	-	
311	43	RCL	
312	30	30	
313	95	=	
314	42	STO	
315	29	29	
316	00	0	
317	32	X:T	
318	43	RCL	
319	29	29	

MERGED CODES

62 63 64 72 STO 73 RCL 74 SUM 83 GTO 84 92 INV SBR

TEXAS INSTRUMENTS INCORPORATED

TITLE PIPELINE DESIGN GENERAL WATER HAMMER ANALYSIS — Appendix 6 — PAGE 1 OF 4

TI Programmable Program Record

PROGRAMMER West NTC/ Larson DATE Jan 1983

Partitioning (Op 17) 6 3 9 3 9 Library Module No Printer PC100C Cards 3 banks

PROGRAM DESCRIPTION

This program provides a detailed analysis of water hammer caused by valve closure. It can be used for any type of pipe material if the user knows the modulus of elasticity. It first prints out the critical closure time (2L/a), then starts at time zero and computes and prints the effective discharge area at the valve, the flow velocity through the valve, the direct pressure wave head, the reflected pressure wave head, and the net surge pressure head. These values are found at intervals of L/a successively until a peak is found. The peak pressure head is finally printed out for the user to compare with the strength of thepipe under consideration. Other valve closing times can be easily calculated by inputting only the new time of closure if all other values remain constant.

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	Set calculator partition	4	2nd	Op	17	639.39
2	Insert magnetic cards	1, 2, 3				1., 2., 3
3	Input pipe diameter (inside) in inches			A		Prts ID
4	Input pipe wall thickness in inches			B		Prts T
5	Input initial design flow velocity in fps			C		Prts VO
6	Input pipe length in feet			D		Prts L
7	Input effective valve closure time in seconds		2nd	A		Prts TC
8	Input Modulus of Elasticity of the pipe material in psi		2nd	B		Prts E
9	Input design pressure head at the valve in feet		2nd	C		Prts HO
10	To begin calculations			E		
	a. Calculator finds critical closure time					Prts 2L/A
	b. Begins at time zero, then progressively to other times					Prts TIME
	c. Finds actual flow area through valve at time t					Prts A
	d. Finds velocity fhrough the valve at time t					Prts V
	e. Finds magnitude of the direct pressure wave head at time t					Prts F+
	f. Finds magnitude of the reflected pressure wave head at time t					Prts F-
	g. Finds magnitude of the net surge pressure head at time t					Prts H+
	h. Finds new time t (multiples of L/a) and recomputes all of the outputs described above. When the value of H+ shows a decrease from the preceding value of H+, calculations stop and the calculator reprints the peak value of H+ and then the total maximum head on the pipe at the valve (H+HO).					

USER DEFINED KEYS	DATA REGISTERS (INV EE)		LABELS (Op 08)
A	0	0	INV lnx CE CLR x⇌t x²
B	1	1	√x 1/x STO RCL SUM yˣ
C	2	2	EE ( ) ÷ GTO ×
D	3	3	SBR − RST + R/S .
E	4	4	+/− =
A'	5	5	
B'	6	6	
C'	7	7	
D'	8	8	
E'	9	9	

FLAGS 0 1 2 3 4 5 6 7 8 9

TLE GENERAL WATER HAMMER ANALYSIS PAGE 1 OF 1

TI Programmable Coding Form

ROGRAMMER DATE

LOC	CODE	KEY	COMMENTS
000	76	LBL	
001	11	A	
002	42	STO	
003	00	00	
004	89	π	
005	65	×	
006	53	(	
007	43	RCL	
008	00	00	
009	65	×	
010	93	.	
011	05	5	
012	54	)	
013	33	X²	
014	55	÷	
015	01	1	
016	04	4	
017	04	4	
018	95	=	
019	42	STO	
020	31	31	
021	02	2	
022	04	4	
023	01	1	
024	06	6	
025	69	OP	
026	04	04	
027	43	RCL	
028	00	00	
029	69	OP	
030	06	06	
031	91	R/S	
032	76	LBL	
033	12	B	
034	42	STO	
035	01	01	
036	03	3	
037	07	7	
038	69	OP	
039	04	04	
040	43	RCL	
041	01	01	
042	69	OP	
043	06	06	
044	91	R/S	
045	76	LBL	
046	13	C	
047	42	STO	
048	02	02	
049	04	4	
050	02	2	
051	03	3	
052	02	2	
053	69	OP	

LOC	CODE	KEY	COMMENTS
055	43	RCL	
056	02	02	
057	69	OP	
058	06	06	
059	91	R/S	
060	76	LBL	
061	14	D	
062	42	STO	
063	03	03	
064	02	2	
065	07	7	
066	69	OP	
067	04	04	
068	43	RCL	
069	03	03	
070	69	OP	
071	06	06	
072	91	R/S	
073	76	LBL	
074	16	A'	
075	42	STO	
076	04	04	
077	03	3	
078	07	7	
079	01	1	
080	05	5	
081	69	OP	
082	04	04	
083	43	RCL	
084	04	04	
085	69	OP	
086	06	06	
087	91	R/S	
088	76	LBL	
089	17	B'	
090	42	STO	
091	05	05	
092	01	1	
093	07	7	
094	69	OP	
095	04	04	
096	43	RCL	
097	05	05	
098	69	OP	
099	06	06	
100	91	R/S	
101	76	LBL	
102	18	C'	
103	42	STO	
104	06	06	
105	02	2	
106	03	3	
107	03	3	
108	02	2	

LOC	CODE	KEY	COMMENTS
110	04	04	
111	43	RCL	
112	06	06	
113	69	OP	
114	06	06	
115	03	3	
116	02	2	
117	93	.	
118	02	2	
119	42	STO	
120	28	28	
121	65	×	
122	02	2	
123	95	=	
124	42	STO	
125	27	27	
126	02	2	
127	03	3	
128	04	4	
129	07	7	
130	42	STO	
131	36	36	
132	02	2	
133	01	1	
134	02	2	
135	00	0	
136	42	STO	
137	35	35	
138	02	2	
139	01	1	
140	04	4	
141	07	7	
142	42	STO	
143	34	34	
144	03	3	
145	07	7	
146	02	2	
147	04	4	
148	03	3	
149	00	0	
150	01	1	
151	07	7	
152	42	STO	
153	22	22	
154	25	CLR	
155	91	R/S	
156	76	LBL	
157	15	E	
158	43	RCL	
159	02	02	

MERGED CODES

62 · 63 · 64 · 72 STO · 73 RCL · 74 SUM · 83 GTO · 84 · 92 INV SBR